Combined heat and power plant electrical equipment incident rate and unavailability empirical expression

Romāns Oļekšijs and Bogdan Olekshii

Abstract

Empirische Kennzahl für Störungen und Nichtverfügbarkeit von elektrischen Komponenten in Heizkraftwerken

In diesem Beitrag wird ein Ansatz zur Abschätzung der Störungsrate und der Nichtverfügbarkeitszeit der elektrischen Haupteinrichtungen eines Heizkraftwerks auf der Grundlage statistischer Daten vorgestellt. Es werden empirische Gleichungen für die Ermittlung der Störungsrate und der Nichtverfügbarkeitszeit von Generatoren auf der Grundlage von Betriebsstunden und der Anzahl von Anlagenstarts pro Jahr aufgestellt. Es wurde ein Überblick über die verfügbaren Störungsstatistiken von Leistungstransformatoren und Generatorschaltern erstellt, und es wurden Gleichungen für die Ermittlung der Gesamtstörungsrate und der ungeplanten Nichtverfügbarkeitszeit der elektrischen KWK-Hauptsysteme aufgestellt. Die so gewonnenen Gleichungen ermöglichen eine Prognose der Störfallrate und der dadurch verursachten Ausfallzeit auf der Grundlage der erwarteten KWK-Betriebszeit und der Anzahl der Anlagenstarts pro Jahr. Diese Informationen sind hilfreich für die Risikobewertung und die Planung von Kraftwerksbetriebsregimen. Die bereitgestellten Gleichungen können für jedes beliebige KWK-Kraftwerk verwendet werden, die Benutzer müssen lediglich eine geeignete Gleichung auf der Grundlage der prognostizierten Betriebsstunden und der Anzahl der Anläufe des Kraftwerks auswählen. Es werden Berechnungsbeispiele vorgestellt. Außerdem wird eine kurze Beschreibung möglicher wirtschaftlicher Parameter gegeben, die für die Wahl des richtigen Betriebsregimes sehr wichtig sind.

Mr Romāns Oļekšijs was awarded the vgbe Innovation Award 2021 | Category: Application-oriented for his work, which is topic of this article. The award ceremony took place during the vgbe Congress in Essen on 22 September 2021.

1 Introduction

Modern combined heat and power plants (CHP) are designed for two-shift operation mode, this type of operating is more damaging for power plant equipment. It is well known, that thermal fatigue is at its most damaging when a component is operating in the creep range and is subject to a constant tensile load. This mostly affects gas turbines and heat recovery steam generators (HRSG). [1][2][3] Thus, the impact on power plant electrical equipment is not studied as much as heat regeneration steam generators and steam turbines. Generator, power transformers and switchgear can be susceptible to increased fatigue, wear, and other forms of degradation due to repeated stop-start operation. [4][5]

VGB presented in [6] that there were around 39 unplanned unavailability incidents per unit per year in average during 2008-2017, leading to 7.7 % of unplanned energy una-

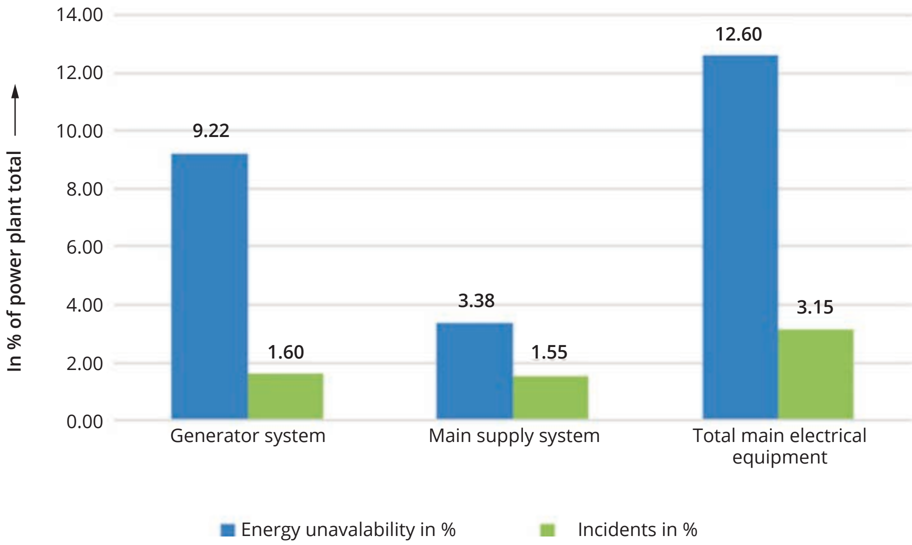

Fig. 1. Impact of main electrical equipment on CCGT power plant unavailability.

Autors

Ph.D. Romāns Oļekšijs
JSC "Latvenergo",
Riga, Latvia
Romans.Oleksijs@edu.rtu.lv

B.Sc. Bogdan Olekshii
Institute of power system
Riga Technical University
Riga, Latvia
Bogdan.Olekshii@edu.rtu.lv

vailability. The precise number of incidents on generators main transformers and circuit breakers is not reported, still, the caused unavailability time is illustrated in Figure 1. Despite that, total incident count for main electrical equipment is only 1.22 incidents per unit per year, which is 3.15 % of all incidents, it causes 0.97 % of unplanned energy unavailability, which is 12.6 % of total power plant unplanned energy unavailability, which shows how high is impact of incidents in power plant main electrical equipment systems.

Around 42 % of unplanned energy unavailability caused by the main electrical equipment is represented by generator incidents. Generator must operate under electrical, mechanical and thermal stress all the time. The majority of problems occur with generator insulation, although, mica insulation has great insulation capability of around 300 kV/m, the imperfections of insulation, such as cracks, voids, delamination, wrinkles or damaged mica layers lead to electrical treeing development and break down of insulation. [7] The main causes of generator failures are problems with stator windings, rotor windings and bearings, thus, no precise statistic is available due to sensitivity of such information [8].

Thus, for other electrical equipment under the scope broad statistics of incident causers is available. Power transformer weakest spots or elements are represented in Figure 2. Usually, problems appear with online tap changers, which are rare for step-up transformers. Problems with windings appear due to local short circuits or short circuits in the grid, as well as lightning strikes. Bushing problems also are common to all power transformers. Other problems are mostly related to the cooling system, wrong operation of relay protection or failure of self-consumption. Failure rate statistic on step-up power transformers is presented in Table 1.

Main circuit breakers cause very few problems for power plants, but their failure can cause long unavailability. [6][10] Usually circuit breaker problem occurs when an operation command is performed. In some case circuit breakers locks and do not perform task operation due to failure or blocking within the circuit breaker control system, such failure mode represents 25 % of failures. Electrical problems are usually related to breakdown to earth, breakdown across the pole or inability to carry flowing current. Problems with the mechanical part are not very common. Even more rare is operation without a command, in 5.4 % failure case circuit breaker opens without command. High voltage circuit breaker failure modes are represented in Figure 3 and failure rate presented in Table 2. [11]

Tab. 1. Step-up power transformer failure rate.

Highest voltage, kV	< 200	200 to 300	300 to 500	500 to 700	>700
Major failures	20	43	89	9	4
Failure rate	0.0059	0.0093	0.0132	0.0049	0.0054

Tab. 2. The number of major failures per command per generatorccircuit breaker technology.

CB type	Failure type	Λcb
Air-blast	Major failure per 10 000 close commands	0.344
	Major failure per 10 000 open commands	0.006
	Total	0.350
SF_6 with pneumatic-operating mechanism	Major failure per 10 000 close commands	0.032
	Major failure per 10 000 open commands	0.028
	Total	0.060
SF_6 with hydro-mechanical spring operating mechanism	Major failure per 10 000 close commands	0.020
	Major failure per 10 000 open commands	0.004
	Total	0.024

2 Approach of incident rate and unavailability evaluation

An incident of a generator, step-up transformer and generator circuit breaker leads to energy unavailability. For risk assessment it is essential to know what effects the appearance of incidents in main electrical equipment of a power plant. In this research, two criteria are used to prognose the incident appearance, these are: the number of operating hours and number of start-ups.

Step-up transformer incidents are not affected by the number of start-ups as well as the number of operating hours, because they are connected to the transmission grid all year long, excluding the maintenance shutdowns. Only incidents, reported for circuit breakers appear during operation commands, so incidents are dependent only on the number of operations. Generator incident rate depends on various factors, which appear only during operation hours and are enforced during transient regime. Figure 4 shows that the generator incident rate is not a regular function of operating hours. The same is if the incident rate is presented as function of start-up number. It is

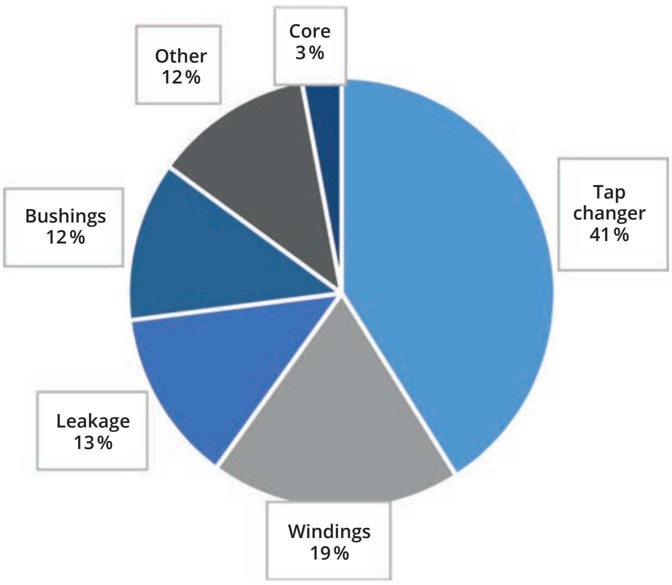

Fig. 2. Power transformer subcomponent failures [9].

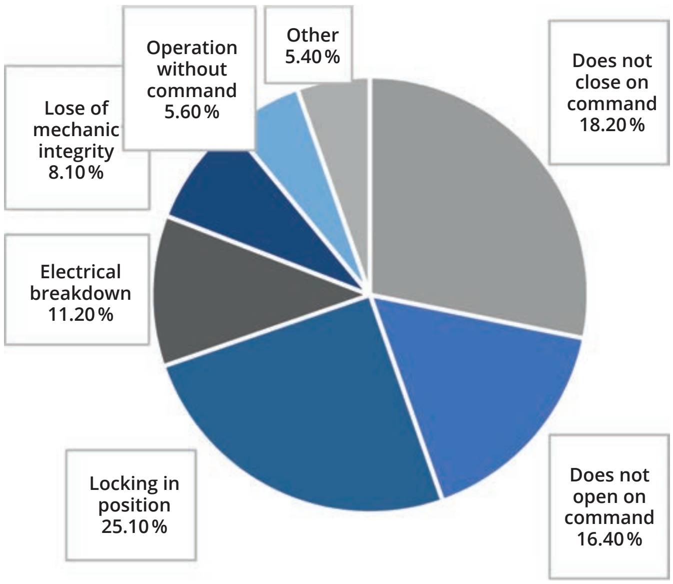

Fig. 3. High voltage circuit breaker major failure modes.

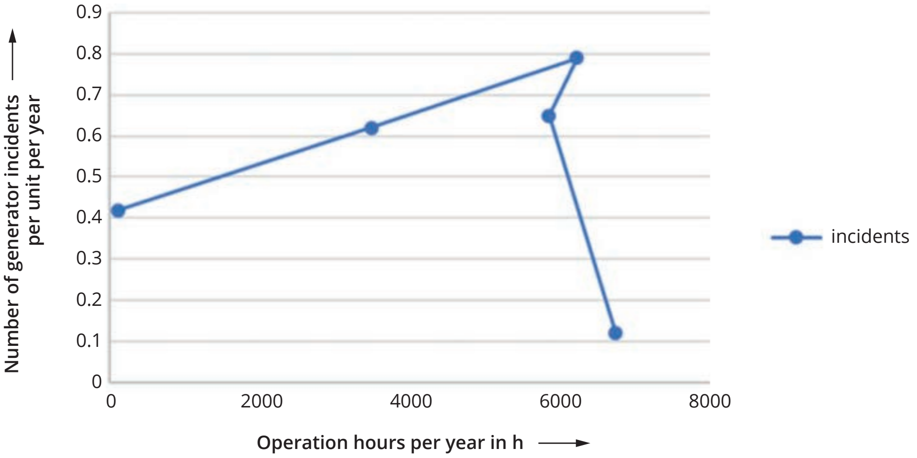

Fig. 4. Number of generator system incident per year per unit relation to operating hours per year.

because of the difference of generator constructions, age and operating regimes represented by statistics, incident rate of generators in generally can be expressed as follows:

$$\lambda_{gen} = f(t_{op}; n_s; c; y; t_t\ldots) \quad (1)$$

where, λ_{gen} – generator incident rate;
t_{op} – operation time per year, h/year;
n_s – number of starts per year, 1/year;
c – cooling method (direct or indirect);
y – insulation technology;
t_t – total number of hours in operation, h; and other factors.

As it is not possible to describe generator incident rate from physical model or it is too complicated to be applied in practice, the empirical model can be used to evaluate relations between different variables (startup number and operating hours) to describe incident rate probability. In this paper, least square method and proposed approach are used to find out empirical formula for turbogenerator incident rate and unplanned unavailability time. [12] Using least square method incident rate would be expressed as:

$$\lambda_{gen.l} = \beta_0 + \beta_1 t_{op} + \beta_2 n_s \#(1)$$

where, $\lambda_{gen.l}$ – incident rate calculated by least square method;
β – unknown parameters of empirical model.

In case if least square method is used expression below will be obtained:

$$\lambda_{gen.l} = -1.92807 + 0.00029 t_{op} + 0.03266 n_s \#(2)$$

In proposed approach for generators we propose to get rid of the number of operating hour or the number of starts, to get more clear dependency of incident rate in one of proposed variables. Used statistics clearly defines average operated hours per year, but the number of start-ups was evaluated from several sources of information [13], [14], so we choose to use operating time as base for further calculation. Hourly incident rate is:

$$\lambda_{gen.h} = \frac{\lambda_{gen.h}}{t_{op}} = \left(\frac{n_s}{t_{op}}\right) \#(3)$$

Such expression also means that the number of starts must be expressed as number of starts per hour. This allows to get relation between incident rate per hour and start-ups per hour which is presented in Figure 5 and seems to have linear relation. Due to much lower operation hours and incident rate, comparing to other technologies, open cycle gas turbine power plant (OCGT) generators statistics differs a lot from other used data. After excluding OCGT data, a nonlinear relation appears between the corresponding parameters. For a better understanding Figure 6 shows lower part of graph (marked by cloud at Figure 5) where fossil fired and CCGT unit statistic appears. [6]

Logarithmic expression could be used to express relation between number of generator system incident per hour per year per unit relation to number of starts per hour per unit per year. But obtained expression will not stick with the existing points of the graph. In case if incident rate is calculated by least square method, obtained results sticks well to used statistics. Thus, errors could appear in some combination of operating hours and number of start-ups per year, incident rate could hit negative values which is presented at Figure 7 and is unacceptable. To avoid such situations, all data presented at Figure 5 were divided in parts which now can be expressed as linear functions. For incident estimation perhour per unit per year Table 3 should be used.

After hourly generator incident rate is calculated for prognosed regime (4), it should be multiplied by prognosed operation hours per year, this will lead to generator incidents

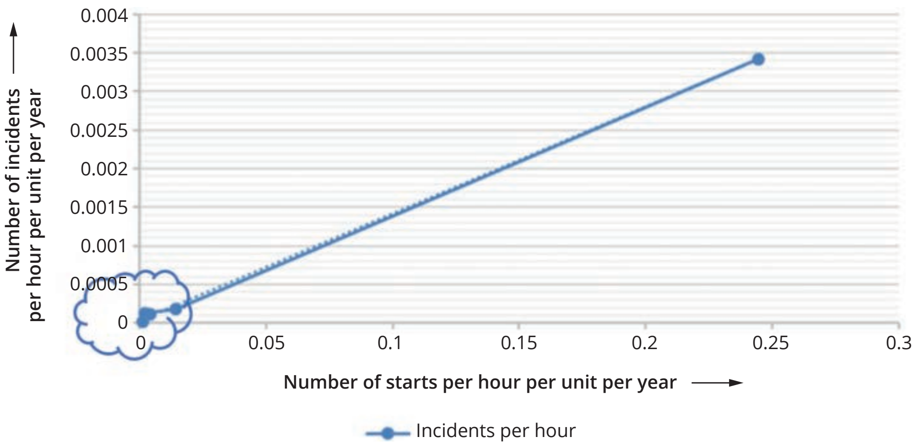

Fig. 5. Number of generator system incident per hour per year per unit relation to number of starts per hour per unit per year.

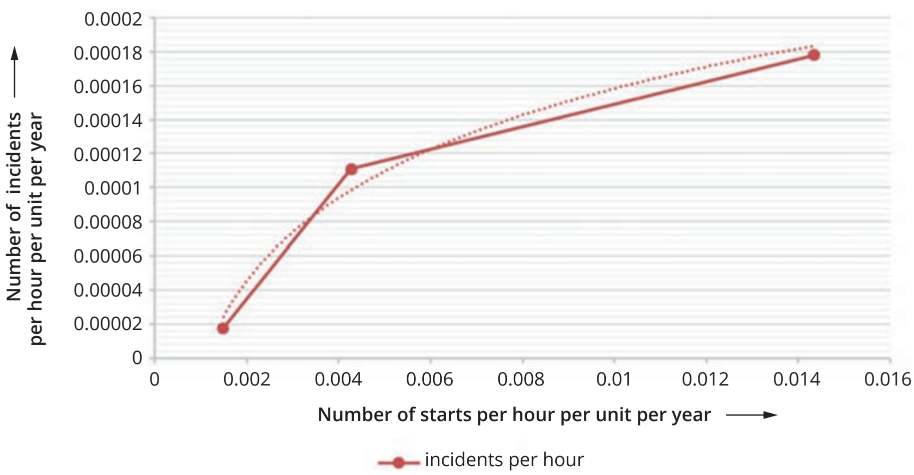

Fig. 6. The number of generator system incident per hour per year per unit relation to number of starts per hour per unit per year excluding OCGT and 200 to 600 MW generator data.

Tab. 3. Equations for Incident Rate Estimation for Generators.

Number of starts per hour per unit per year	Estimation equation	Equation number
0.000741 to 0.004272	$0.0264*n_{s.h} - 0.000002$	1
0.004272 to 0.014341	$0.0066*n_{s.h} + 0.00008$	2
0.014341 to 0.570776	$0.0058*n_{s.h} + 0.00009$	3

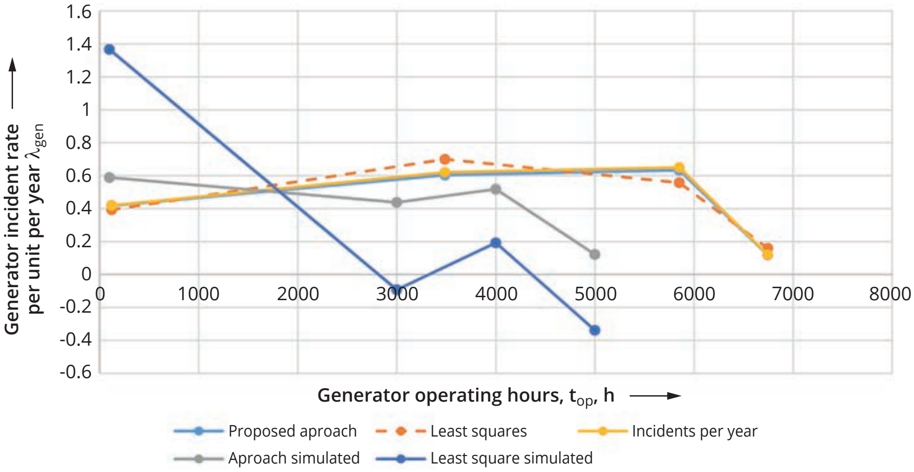

Fig. 7. Comparison of prosed approach results and least square results for generator incident rate estimation.

Tab. 4. Generator Incident estimation.

Prognosed operating hours per year	Prognosed starts per year	Starts per hour	Equation number	Incidents per year
2000	10	0.005	2	0.226
2000	30	0.015	3	0.354
2000	100	0.05	3	0.760
3000	10	0.0033333	1	0.258
3000	30	0.01	2	0.438
3000	100	0.0333333	3	0.850
4000	10	0.0025	1	0.256
4000	30	0.0075	2	0.518
4000	100	0.025	3	0.940

per unit per year. Calculation is made using (5) and Table 3. The example result is provided in Table 4. It is clear, that the number of star-ups affects incident rate immensely, operating hours have much lower impact on incident rate, at low start-up number, increase of operating hour results in a slight decrease of the incident rate. Thus, at a moderate or a high number of starts, the increase of operating hours will lead to a higher incident rate of a generator.

$$\lambda_{gen.h.3} = 0.0058 * \frac{n_s}{t_{op}} - 0.00009 \#(4)$$

where, $\lambda_{gen.h.3}$ – generator incident rate per hour per unit per year calculated by equation number 3 from Table 3.

$$\lambda_{gen} = \lambda_{gen.h} * t_{op} \#(5)$$

where, λ_{gen} – generator incident rate per unit per year;

$\lambda_{gen.h}$ – generator incident rate per hour per unit per year calculated by (4).

Power transformer incident rate will be taken from [9]. The number of power transformers in one power plant unit must be observed as well as the transformer highest rated operating voltage, because incident rate statistics is provided for different voltage levels. For circuit breakers, data from [11] will be used. To evaluate circuit breaker incident rate per unit per year a number and type of circuit breakers must be observed. Total power plant unit main electrical equipment incident rate is calculated as follows:

$$\lambda_{el.t} = \lambda_{gen} + \lambda_t + \lambda_{cb} = \lambda_{gen.h} * t_{op} + \sum_{i=1}^{n} \lambda_{t.v} + n * \sum_{i=1}^{n} \lambda_{cb.t} \#(6)$$

where, $\lambda_{el.t}$ – main electrical equipment total incident rate per unit per year;

λ_{gen} – generator incident rate per unit per year calculated by (5);

λ_t – step-up power transformer incident rate per unit per year;

λ_{cb} – generator circuit breaker incident rate per unit per year;

n – total amount per power plant unit;

$\lambda_{t.v}$ – step-up transformers incident rate according to voltage level of step-up transformer;

$\lambda_{cb.t}$ – generator circuit breaker incident rate according to circuit breaker technology.

Total main electrical system incident rate calculation results are shown in Table 5, for CHP in Baltic state it is common to use 110 kV and 330 kV step-up transformers for one power plant unit, for circuit breaker SF_6 with hydro-mechanical spring operating mechanism technology was chosen.

Step-up transformer caused power plant unit unavailability percentage is reported in wide range even for VGB power plants, its value varies in 0.02-0.12 % range of total hours per year. For generators unavailability indicator lies in 0.12-1.29 % range of total hours per year. For generator incident caused unavailability percentage estimation, the same approach will be used that was used for generator incident rate estimation.

$$k_{un.h} = \frac{k_{un}}{t_{op}} = f\left(\frac{n_s}{t_{op}}\right) \#(7)$$

where, $k_{un.h}$ – hourly energy unavailability percent per unit per year, %.

Tab. 5. Power plant unit main electrical equipment incident estimation.

Prognosed operating hours per year	Prognosed starts per year	λ_{gen}	$\lambda_{t.110}$	$\lambda_{t.330}$	λ_{cb}	$\lambda_{el.t}$
2000	10	0.226	0.0059	0.0132	0.0000048	0.2451
2000	30	0.354	0.0059	0.0132	0.0000048	0.3731
2000	100	0.760	0.0059	0.0132	0.0000048	0.7791
3000	10	0.258	0.0059	0.0132	0.0000048	0.2771
3000	30	0.438	0.0059	0.0132	0.0000048	0.4571
3000	100	0.850	0.0059	0.0132	0.0000048	0.8691
4000	10	0.256	0.0059	0.0132	0.0000048	0.2751
4000	30	0.518	0.0059	0.0132	0.0000048	0.5371
4000	100	0.940	0.0059	0.0132	0.0000048	0.9591

Tab. 6. Equations for unavailability estimation for generators.

Number of starts per hour per unit per year	Unavailability % estimation equation	Equation number
0.000741 to 0.004272	$0.0148 * n_{s.h} + 0.000007$	1
0.004272 to 0.014341	$0.0133 * n_{s.h} + 0.00001$	2
0.014341 to 0.570776	$0.0204 * n_{s.h} - 0.00009$	3

Tab. 7. Equations for unavailability estimation for generators.

$\lambda_{el.t}$	k_{un} generator, %	k_{un} transformers, %	k_{un} total, %	Unavailability hours, t_{un}
0.245105	0.153	0.12	0.273	23.92
0.373105	0.432	0.12	0.552	48.36
0.779105	1.86	0.12	1.98	173.45
0.277105	0.169	0.12	0.289	25.32
0.457105	0.429	0.12	0.549	48.09
0.869105	1.77	0.12	1.89	165.56
0.275105	0.176	0.12	0.296	25.93
0.537105	0.439	0.12	0.559	48.97
0.959105	1.68	0.12	1.8	157.68

Obtained equations are presented in Table 6, equation (5) must be used to get from hourly unavailability percentage to yearly. The next step is calculation of unavailable or unproduced energy due to estimated incident rate. This is done using (8). The loss of a generator, a transformer or generator circuit breaker leads to the loss of full power, so outage hours caused by incidents in main electricity system of power plant can be calculated, the results are represented in Table 7. Unavailability caused by circuit breakers is less than 0.01 % of unavailability caused by generators and power transformers, and is not represented.

$$W_{un.e} = k_{un.e} * P_N * t_N \# (8)$$

where, $W_{un.e}$ – estimated unavailable energy per unit per year due to generator incidents, MWh;

$k_{un.e}$ – estimated incident caused energy unavailability percent, %;

P_N – power plant nominal power, MW;

t_N – calendar time, h. [6]

Literature analysis shows that the number of major incidents, leading to generator or power transformer overhaul, is negligible, thus when such incidents appear, costs and unavailability time of power plant unit become extremely significant.

3 Impact on power plant operation costs

Incidents of electrical equipment and caused unavailability leads to economical loss for power plant and impacts total operation costs. Costs of unplanned unavailability could be divided in two groups, first – additional maintenance and repair costs; second – loss of income due to incident. It could be expressed as follows:

$$C_{un} = \lambda_{el.t} * (C_{mr} + C_s) + t_{un} * P_{CHP} * (C_{el} + C_{bal}) \ (9)$$

where, C_{un} – unavailability costs, EUR;

C_{mr} – maintenance and repair costs due to incident in main electrical system. EUR/cycle;

C_s – power plant start-up costs, EUR/cycle;

t_{un} – unplanned unavailability per year, h;

P_{CHP} – power plant installed active power, MW;

C_{el} – costs of loss due to undelivered electricity, EUR/h;

C_{ser} – costs of loss due to undelivered services, EUR/h;

C_{bal} – balancing costs, EUR/h.

Mentioned costs can vary in wide range due to region, type of power plant, legislation and other factors. Any of mentioned costs are not often reported, because it is sensitive information for electricity generators and manufacturers of generators and power transformers. In [15] generators incident costs were reported as high as 140,794 EUR, but [16] reported only 23,500 EUR per incident. Costs of balancing energy in 2018 in Latvia were 59.27 EUR/MWh and electricity market price were 49.90 EUR/MWh.

Using data from Table 5 and Table 7 calculations of (9) basing on data from [15] were made to show possible financial impact of unplanned incidents in main electrical equipment on 400 MW combined heat and power plant. Results are presented in Table 8.

Tab. 8. Financial loss due to CHP main electrical equipment incident and unavailability.

Prognosed operating hours per year, h	Prognosed starts per year	$\lambda_{el.t}$	Unavailability hours, tun	Yearly loss, EUR
2000	10	0.24511	21.4712	1,236,334
2000	30	0.37311	32.6840	2,362,840
2000	100	0.77911	68.2496	8,013,303
3000	10	0.27711	24.2744	1,312,350
3000	30	0.45711	40.0424	2,390,242
3000	100	0.86911	76.1336	7,710,680
4000	10	0.27511	24.0992	1,338,201
4000	30	0.53711	47.0504	2,465,522
4000	100	0.95911	84.0176	7,408,056

4 Conclusion

To make approach of incident rate and unavailability evaluation, numerous statistics were analyzed. Available statistics for generator system represent only incidents and caused unavailability data, thus do not provide data on major incidents. For power transformers, more incident data is available, but there is almost no statistics for caused outage. Generator circuit breaker incident markers are so low, that caused unavailability was not considered in final calculations. Obtained empirical equations for incident rate of generator and caused unavailability time evaluation were presented. Expressions considers the number of operated hours per year and number of starts per year for CHP. Also, data for power transformer and circuit breaker incident rate evaluation is presented.

The increase of number of start-ups leads to the increase of incident rate and unavailability time. In some cases, the increase of operating hours at same start-up level can lead even to lower incident rate and unavailability percentage. Also, economical effect of incident rate and unavailability hours were studied. Such approach is indicative and should help in risk assessment. As a result, proper operating regimes could be selected as well as the best investment strategy (improved monitoring and/or upgrades) could be chosen based on the foreseen CHP operation regimes.

References

[1] C.H. Lee; Zainul Asri Mamat, *Investigation of Performance Degradation for TNB Newly Commissioned Combined Cycle Power Plant Case study at PD1.* 2009 3rd International Conference on Energy and Environment (ICEE), 7-8 Dec. 2009, Malacca, Malaysia.

[2] Gulen S.C. *Gas Turbine Combined Cycle Fast Start: The Physics Behind the Concept* . Power engeneering magazine 06.12.2013.

[3] Baling L. *Fast cycling and rapid start-up: new generation of plants achieves impressive results*. Modern power systems January 2011.

[4] M. Baca, *Extended requirements on turbo-generators due to changed operational regimes*. VGB Congress 2015, Vienna.

[5] Maughan C. *Premature failure of modern generator*. 2012 20th International Conference on Nuclear Engineering, July 30–August 3, 2012 Anaheim, California, USA.

[6] *Technical scientific report Analysis of unavailability of power plants 2008-2017*. VGB PowerTech Service GmbH, 2018, Essen, Germany.

[7] Bruetsch M., Tari M., Froehlich K., Weiers T., Vogelsang R. *Insulation failure mechanism of power generators.* IEEE electrical insulation magazine vol. 24. 2008.

[8] C.V. Maughan, *“Root-cause diagnostics of generator service failures”.* IEEE International Conference on Electric Machines and Drives, 2005., San Antonio, TX, 2005, pp. 1927-1935.

[9] CIGRE Working Group A2.37, *“TRANSFORMER RELIABILITY SURVEY,”* CIGRE TB 642, Dec. 2015.

[10] NERC (North American electrical reliability corporation) report *“State of reliability 2018”* https://www.nerc.com.

[11] C. Antoun *High Voltage Circuit Breaker and Power Transformer Failure Modes and Their Detection.* 2018 Condition Monitoring and Diagnosis (CMD) 23-26 Sept. 2018, Perth, WA, Australia.

[12] D.C. Montgomery, G.C. Runger *“Applied statistics and probability for engineers”*. 3rd edition, John Wiley and Sons, 976 p., 2003.

[13] C. Perez Linkenheil, I. Küchle, T. Kurth and F. Huneke *Flexibility needs and options for Europes future electricity system,* September 2017, Berlin, Germany.

[14] M. Kunickis, M. Balodis, O. Linkevics, P. Ivanova, *Flexibility options of Riga CHP-2 plant operation under conditions of open electricity market*. IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG), Riga, Latvia, 2015.

[15] K.Dahala, K. Al-Arfajb, K. Paudyal, *Modelling generator maintenance scheduling costs in deregulated power markets,* European Journal of Operational Research, vol. 240, Issue 2, pp. 551-561January 2015

[16] N. Kumar, P.M. Besuner, S.A. Lefton, D.D. Agan, D.D. Hilleman, *Power plant cycling costs,* Intertek APTECH, www.intertek.com/aptech.