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RESULTS OF THERMOGRAPHIC DIAGNOSTICS OF ELECTRIC GRID CONTACT JUNCTIONS AND GENERATORS OF OIL SHALE POWER PLANTS

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Thermographic monitoring allows implementation of the diagnostics of electrical equipment on the higher technological level comparing with the conventional methods. The methods of thermographic (infra-red) diagnostics of high-voltage electric grid contact junctions and electrical generators of oil shale power plants of Eesti Energia Ltd are described in the paper. The analysis of the measurement and fault data is given as well. The results of the research enable to compose the plans for preventive maintenance and scheduled repairs of the electric equipment. Thermographic diagnostics saves substantial financial and material resources and increases the reliability of power supply.

Introduction

One of the major tools for maintaining the reliability, safety and profitability of power systems is wider introduction of modern technologies in the evaluation of technical conditions of power installations. Among the most commonly used methods for evaluating the condition of a power system, the infra-red thermographic method has been increasingly used over the past years.

Despite of the high cost of infra-red thermographic inspection hardware, the number of thermal cameras in operation has increased annually. This kind of big investment is justified by the wide range of possibilities offered by thermographic monitoring in early diagnostics of power installations. This concerns especially high-voltage electrical installations, the breakage of which can cause large costs concerning reparation or replacement of defected installations, which can also be a reason for long-term interruptions in power supply for important consumers.

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Although termographic diagnostics is the most modern method for evaluating the condition of electrical installations, it is also the most expensive one. It enables to control the entire set of electrical installations such as energy transformers, measurement transformers, contacts of disconnectors, bushings of circuit-breakers and transformers, all rigid insulators, suspension insulators of the lines, and practically all other contacts of the substation including panels of auxiliary consumption and relay protection.

At the same time the situation in infra-red thermography is characterized by shortage of information regarding the experience in the inspection of objects. This results in low efficiency of using expensive equipment, errors in evaluating the actual condition of the equipment and, consequently, breakages in the electric equipment.

The current paper studies the methods of thermographic (infra-red) diagnostics of electric grid contact junctions and electrical generators of oil shale power plants of *Eesti Energia* Ltd. and analyses the measurement and fault data.

Inspection of Disconnectors and Contact Junctions

At disconnectors the possible heating is mostly located in contact junctions, therefore a common method for thermographical inspection can be used [1, 2].

During thermographical inspection of the electric equipment of lines and substations most heating cases have been detected in contact junctions, and this applies to Estonia and abroad. Therefore the heating of contact junctions is the most vital theme for power systems, as the damages of defective contact junctions which have not been detected in time form the major part of all damaged equipment.

The existing methods do not enable to guarantee preventive maintenance of contact junctions. These contact junctions include mostly the junctions of contacting busbars and electrical equipment.

This is the area where most experience has been gathered [3–5], as the diagnostics of contact junctions on the basis of their temperature was applied long before thermal cameras and thermographical diagnostics method. Temperature of contact junctions was measured with thermal candles, special thermometers, thermopaints, thermoindicators, etc. The easiest method used by operational staff of power systems was visual observation of the changes of color in contact junctions, steaming of contact junctions during rain, absence of hoarfrost during the first colds.

The use of thermal cameras in determining the defects in contact junctions is based on the fact that the temperature of contact junctions is directly connected to the resistance, i. e. the deterioriation level of the defect. The amount of heat emitted from the contact junction is proportional to the relevant resistance and equal to the square of the electric current passing through the contact junction. The emergence of a defect in contact junction results in the increase in its resistance and, accordingly, in the raise in temperature.

The equation of a thermal equilibrium for contact junction:

$$0.24 \cdot I^2 \cdot (R_k - R_l) = \alpha_{ef} \cdot (T_k - T_l) \cdot F_k \tag{1}$$

where I – electric current in the busbar, A;

R_k – contact resistance, Ω;

R_l – the resistance of busbar (without the contact), Ω;

T_k, T_l – temperatures of contact and the busbar, K;

F_k – square of contact radiating surface, m^2;

α_{ef} – radiation value of contact and bus surface, W/m^2K.

The resistance of the bus part can be calculated knowing its length, which is equal to the length of contact surface:

$$R_l = \frac{\rho \cdot L}{S} \tag{2}$$

where ρ – bus material resistivity, Ω·m;

L – length of the bus part, m;

S – bus cut area, m^2.

Contact resistance is determined setting different values to defect factor:

$$K_d = \frac{R_k}{R_l} \tag{3}$$

The contact radiating surface area is determined as the sum of all lateral areas of the contact:

$$F = (2 \cdot l \cdot b + 6 \cdot b \cdot h) \tag{4}$$

where l, b and h – length, breadth and thickness of the bus part forming the contact junction.

In case the rated current and defect factor are rationed 20% (K_d = 1.2), the temperature of contact junction is a few degrees above the temperature of the bus. For example, the temperature of contact junction of aluminium bus of the size (60 × 60 × 6 mm) in rated current I_n = 870 A will be ΔT = 1.3 °C.

The evaluation of contact junction conditions is made by comparison of temperatures of the same type of contacts in identical load and cooling conditions. The inspection can also be made comparing the temperatures of contact junction and the conductive part of the bus.

While monitoring contact junctions, thermal camera has to be located as close as possible. That will allow receiving more precise information about the defect location. The distance of 30–40 m is the limit for measuring the temperature of contact junction.

Thermographic measurements should be conducted in favourable climate conditions, i.e. during the months when air temperature does not exceed

+15 °C, when there is no rain or snow, under cloudy sky. The wind velocity should not exceed 4 m/s. The temperature values measured should be corrected considering the load, radiant emmitance of measured objects and climate conditions.

For example, for oxidized copper K_{em} = 0.95, aluminium K_{em} = 0.75, for closed switchgears K_{em}= 0.70. Radiation values of non-oxidized metals are extremely small (0.02 for copper and 0.04–0.07 for aluminium) and metal consistency relatively significant, therefore it is impossible to get precise results in the case of new switchgears. Even more complications are caused by the brilliance and reflection of new buses.

Efficiency of detecting defects in contact junctions depends from the magnitude of the current during inspection. Therefore it is necessary to carry out inspections at loads close to the nominal values. It is not recommended to carry out inspections if the working load is less than 50% of the nominal load, as the probability of finding defects is considerably lower.

During thermal inspection of contact junctions we have noticed the interdependency between the number of defective contact junctions and the voltage of an electrical installation: the largest number of defective contact junctions has been detected in 6–10 kV switchgears. The greater the voltage, the fewer the number of defects. This can be explained by the differences in the working conditions of contact junctions regarding the load and cooling, and also by the operation quality.

It is necessary to mark that the absolute majority of thermal camera users use the cameras mainly for inspection of contact junctions, although the range of possibilities for using thermal cameras when inspecting high-voltage electrical installations is much wider.

The following criteria can be used for rejection of contact junctions:
$\Delta T < 5$ °C – the contact is in a normal condition;
5 °C $< \Delta T <$ 35 °C – the contact needs to be inspected during the main repairs;
35 °C $< \Delta T <$ 85 °C – the contact needs repairs during the day-to-day repairs;
$\Delta T > 85$ °C – the contact needs extra repair during three months.

Here ΔT – difference in the bus and contact temperatures, or the difference in analogous contact junction temperatures, which is reduced on nominal voltage using the following ratio I_n:

$$\Delta T = \Delta T_m \left(\frac{I_n}{I_m} \right)^2 \tag{5}$$

where I_n – rated current of the bus, A;
I_m – current, at which the temperature of contact is determined, A.

They are rationed as follows [1] – bus conclusion from copper, aluminium and their alloys (foreseen for external posting of electrical circuits):
– without cover 90 °C (max heat), 50 °C (excessive temperature)
– with cover (Sn, Ag or Ni) 105 °C (max heat), 65 °C (excessive temperature)

An example of overheated contact junction is depicted in Fig. 1.

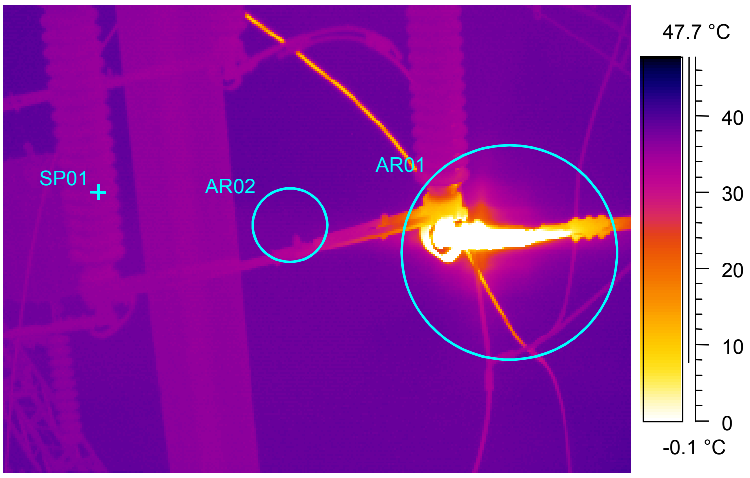

Fig. 1. Contact junction of 110 kV disconnector overheated by fault (over 100 °C)

Thermographic Inspection of Generator Stator Iron

The first tests of active steel are carried out on all generators with the capacity of 12 MW and higher, which have been in operation for more than fifteen years, and then after every 5–8 years; on hydrogenerators such tests are carried out after each removal of the rotor [6]. The tests are also carried out in the case of stator iron damage, full or partial wedging on a winding, or the full replacement of a stator winding before its installation and after wedging.

Generators with less power than 12 MW are tested on full replacement of a winding and repair of stator iron, also periodically once per ten years.

Generators with indirect cooling and synchronous equalizers are tested on stator inductance equal to 1 ± 0.1 *T*; generators with direct cooling and all other generators made after a 1977 at inductance equal to 1.4 ± 0.1 *T*. The duration of test at inductance 1.0 *T* is 90 minutes, at inductance 1.4 *T* – 45 minutes.

If the inductance differs from the standard value by 1.0 or 1.4 *T*, the duration of test should be accordingly changed, and the specific losses determined through the test should be calculated using the following formulas [6]:

$$t_{test} = 90\left(\frac{1.0}{B_{test}}\right)^2 \text{ or } t_{test} = 45\left(\frac{1.4}{B_{test}}\right)^2 \qquad (6)$$

where B_{test} – inductance value during test, *T*;
t_{test} – duration of the test, min.

Heating of stator iron cogs can be determined using the thermal camera (the increase in temperature at the end of the test compared to the initial temperature) and temperatures of different cogs should not exceed 25 °C and 15 °C, respectively.

For example, at the company *Narva Power Plants* the periodicity of such tests is once in six years.

It is interesting to mark that the analogous method for testing stator windings used in Estonian Power Plant differs from a similar test used in Baltic Power Plant. The following example shows the organization of generator stator tests in Baltic Power Plant.

Baltic Power Plant has been in operation since 1959, and all generators are older than fifteen years. Stator iron tests form an integral part of each overhaul of the generator. The tests are carried out in case there is a stator steel damage, full or partial wedging of grooves of a stator winding, full or partial replacement of a stator winding before stacking and after wedging of a new winding.

The difference in the tests results from the application of a unique installation called IZG (test of generator iron). The given test facility developed by the staff of electric department of Baltic PP has been successfully used for several years. The connection scheme of IZG is presented in Fig. 2.

The main specific feature of this equipment lies in regulating the voltage of magnetic winding wound on the stator iron. Secondly, the installation uses power supply from 6 kV switchgear along the 6.3 kV busbar, which passes through the auxiliary transformer and further on through the generator busbar until it reaches the IZG installation.

Remote control of the power switch can be used directly from the generator at the testing location. Two lamps will inform about the position of the switch at 6 kV. The installation is controlled through the control cable from generator into a seering control. The installation enables to perform the tests of both large – 200 and 100 MW, and small generators – 12 MW.

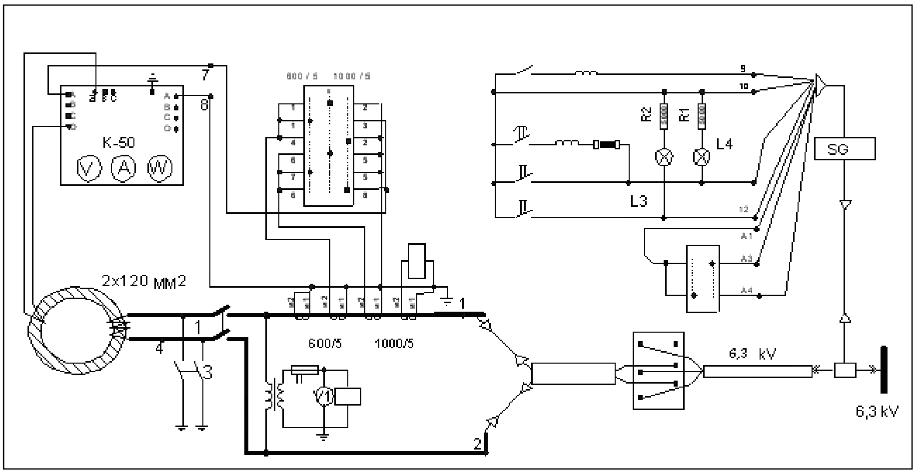

Fig. 2. Connection scheme of test equipment IZG

Fig. 3. Search for hot spots by hand and pyrometer

Fig. 4. Electric generator TBB-200-2A of Estonian Power Plant opened for inspection

Whereas in earlier times the maximum heating of stator iron was tested manually or with the help of pyrometers (see Fig. 3), the presently used termographic equipment enables testing at a considerably higher technological level.

Generally the temperatures determined manually cannot be lower than 40 °C. Only 10–25% of defects can be heated up to this temperature. This means that the majority of defects will be left undetected. Unfortunately, these defects can occur before the next overhaul of the generator, which can be in 6–7 years, which is much longer than the expected period of the defect development (maximum 1–2 years).

The main advantage of using thermographic equipment lies in the possibility of detecting the latent part of defects. Thermal camera is even capable of detecting stator iron defects, which actually do not affect the operation of the generator. Thermal camera gives ten times more information compared to the methods used previously, and enables to get a complete overview of the stator iron heating. Thermographic inspection can also evaluate the quality of repairs with maximum precision.

Examples of thermographic inspection are presented in Figures 4–6.

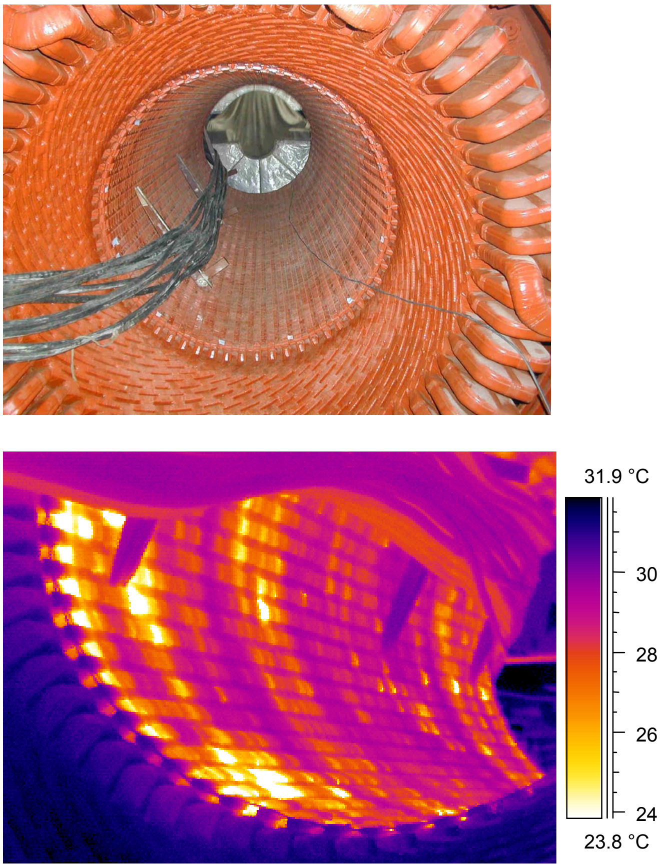

Fig. 5. Inspection result of stator winding

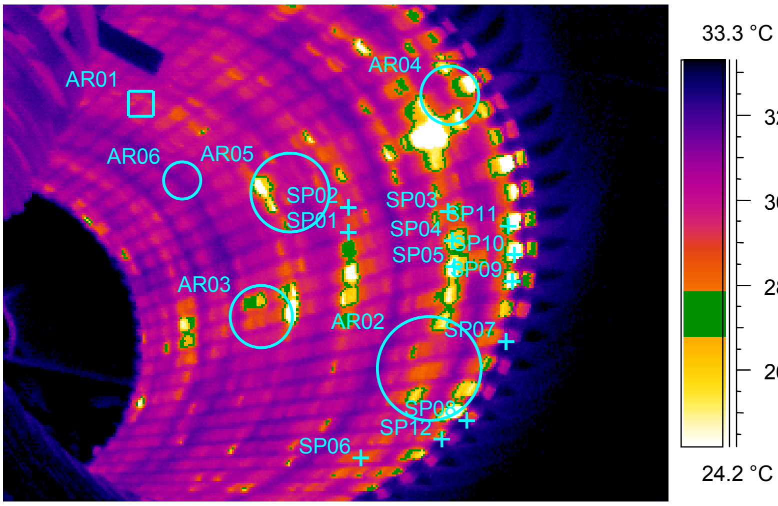

Fig. 6. Overheated spots of stator winding

Analysis of the Results of Electrical Equipment Thermographical Control

Reliability of the electric system is guaranteed mainly through modern construction solutions, reliable methods of diagnostics and realization of scheduled repairs. Quantitative evaluation of the reliability is extremely necessary for planning repairs, analysis of defects of the equipment and timely realization of diagnostic measures. Reliability and working age of electric equipment in substations can be evaluated based on the earlier data on defects.

Thermographical diagnostics should solve two tasks: the first one concerns the realization of the diagnosis of technical condition, the second one is directed towards achieving the main task – technical condition forecast.

The aim of diagnostics is to determine the location of the defect, to establish the reason of the defect and to control technical condition. The aim of the forecast is to define technical condition within the given probability for the forthcoming time period.

According to some normative documents [7, 8], the parameters of reliability should be determined through statistical analysis, which allows to estimate specific features of operating the electric equipment, technical quality of electric equipment in various substations and to predict the condition of their elements.

According to the existing normatives used in the world practice [9], every single detected defect of electrical installation should be considered failure of the system, which needs to be liquidated as a result of appropriate repairs.

Statistical analysis of the results of thermographical control allows not only to allocate objects, which have high or low parameters of operation reliability, but also to pay attention to the equipment, which has the tendency of decreasing reliability.

Usually thermographical control of an electrical equipment with 110–330 kV voltage allows to determine heated contact connections, which further on will be referred to as defects or hot points. In our judgement, one simplification should be made in evaluating the reliability – all found defects should be considered damages of contact junctions (these damages consist approximately 90–95% from all found defects).

Taking into account this simplification we claim that the reliability of all contact junctions of electric equipment on the National Grid substations can be also described by the standard statistical functions. The total number of 110–330 kV voltage contact junctions in substations is measured in thousands, the number varies from several hundreds in smaller substations up to several thousands in bigger ones.

The number of contact junctions in all 110–330 kV substations of National Grid and the total number of detected defects during the period of 1998 for 2003 (divided by classes of defects) have been calculated using the account system of electric equipment of each substation in standard units used in national energy company *Eesti Energia* Ltd. until 1995.

This particular system was used in *Eesti Energia* Ltd. since 1986 according to the former directives of the Ministry of Power Engineering of USSR to calculate the total number of standard units of electric equipment in all substations. The system allowed comparing substations of different sizes. If all found defects are taken equal to 100%, it is possible to calculate the percentage of defects separately for each defect class and to estimate the tendencies of their development over the years. These figures are given in the Table and Fig. 7.

Distribution of Thermographical Defects in the Main Grid by Defect Classes, %

Year	Amount	C-class	B-class	A-class
1998	303 (100)	67 (22)	136 (45)	100 (33)
1999	423 (100)	92 (22)	213 (50)	118 (28)
2000	546 (100)	159 (29)	279 (51)	108 (20)
2001	271 (100)	65 (24)	159 (59)	47 (17)
2002	245 (100)	64 (26)	147 (60)	34 (14)
2003	225 (100)	63 (28)	139 (62)	23 (10)
Total	2013	510	1073	430

The received diagrams show that during the period 1998–2003 there was a constant growth in the number of C-class (weak heating) and B-class (average heating) defects, and a constant decrease in the number of A-class (emergency heating) defects. This means that the number of defects eliminated during scheduled and not-scheduled repairs is constantly growing and the number of defects able to cause emergency switch-off is constantly reduced.

Experimental data, gathered during the last six years from all contact junctions in the substations of National Grid, allow to calculate the average probability value of non-failure operation of the electric system $P_{average}(T)$ using the following formula:

$$P_{average}(T) = \frac{\sum P_i(T)}{N} \tag{7}$$

where $P_i(T)$ – probability of non-failure operation of a single object (substation);
N – total number of objects.

Average probability value of non-failure operation of contact junctions in all substations of National Grid $P_{average} = 0.992 \pm 0.005$. This is equal to the defects flow $\lambda = 0.008$. The number of defects B and C-class is constantly growing. $P_{averageB} = 0.995(\lambda = 0.04)$ and $P_{averageC} = 0.998(\lambda = 0.02)$. The number of A-class defects is constantly reduced – $P_{averageA} = 0.998(\lambda = 0.02)$. Analysis shows that the probability value of non-failure operations in all kind of defects is constantly growing.

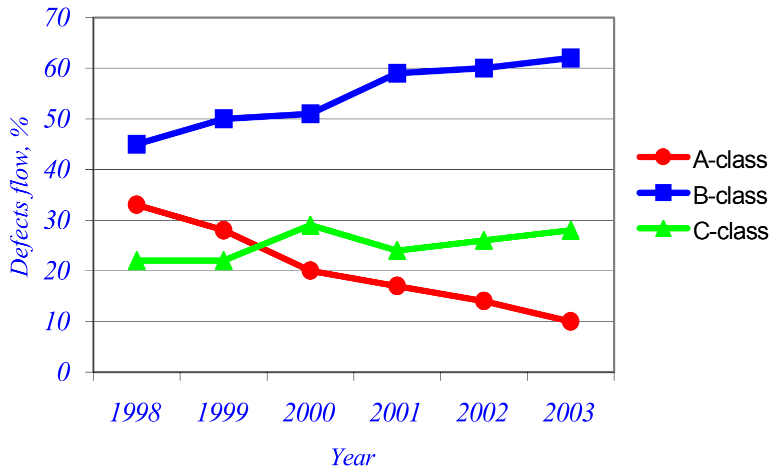

Fig. 7. The probability value of non-failure operation of all contact junctions in the national grid

The formula (7) for experimental estimation of defect probability was given above. This parameter is not sufficient for estimating the reliability of an electric equipment.

Here the method of reliability intervals can be used. It allows estimating the probable mistake and shows the respective borders (upper and lower) for probability of unknown defects at reliable probability δ [10].

An example of reliability intervals of non-failure operation of a typical substation is presented in Fig. 8.

The results of this calculation usually show large dispersion caused by large variety of the legitimate factors [11]. Thus, the results of thermographical inspection require careful processing in order to compare the data from the point of their reliability. It was noticed [12, 13] that the most complicated problems in examining the reliability of electric system elements are caused by the joint processing of all statistical operation data, as it is almost impossible to define the working mode of the switchgear equipment and the identity of conditions by simple analysis. That is why the joint processing of assembled information has to be preceded by determining the randomness of statistic data dispersion.

The non-random character of statistical data dispersion indicates the presence of considerable differences in working modes and conditions of substations. This means that the characteristics of reliability in the substations are relatively different.

Statistical analysis of the assembled data is conducted using the well-known hypotheses of statistical mathematics in order to achieve exact results of joint processing. These hypotheses are divided into several basic types and are given in different publications [12].

The Kolmogorov's criterion was chosen here, and it was applied to the thermographic inspection data from one typical National Grid substation.

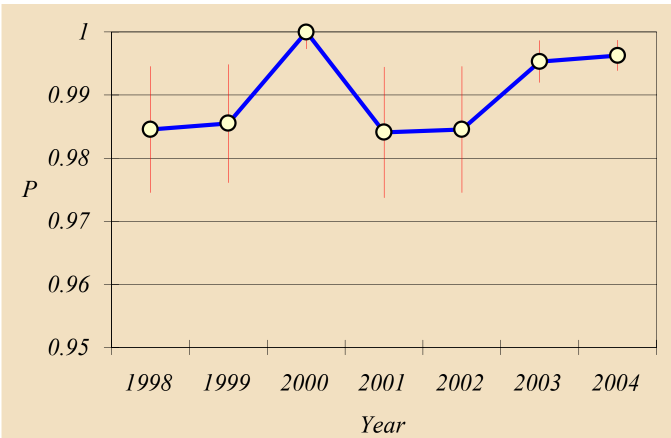

Fig. 8. Reliability intervals of probability of non-failure operation of a typical National Grid substation

We checked the hypothesis of exponential distribution of a defect flow using Kolmogorov's criterion and reached the result that the hypothesis about exponential character of the distribution function is correct [14].

An example of the distribution of the flow of defects is presented in Fig. 9.

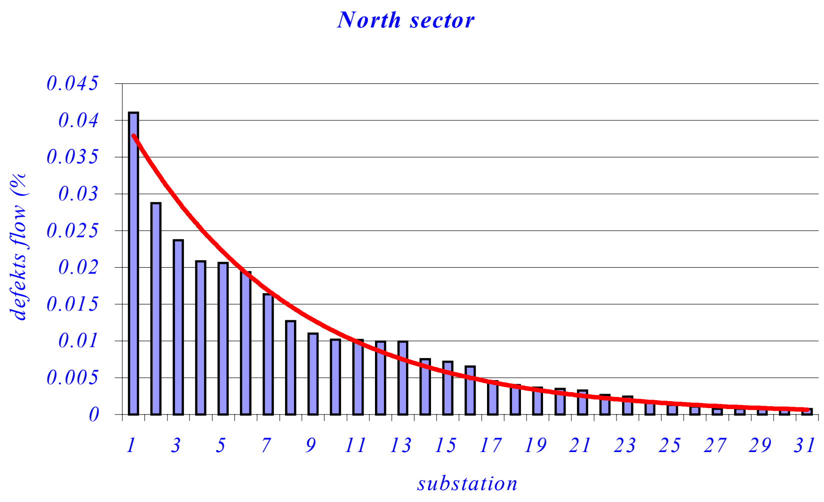

Fig. 9. Distributions of the flow of defects in one sector of National Grid

We can conclude that:

1. Thermographical inspection is a very effective method for determining the reliability of electric equipment.
2. Thermographical inspection results have to be processed using statistical methods. It enables to compare the received data by years in substations of different sizes.
3. Statistical processing of thermographical inspection results allows removing subjectivity of the approach in defining the reliability of electric equipment in substations. It also helps to calculate the optimal time limits of service and thermographical inspection.
4. The analysis of defects discovered by thermographical diagnostics proves the argument that the probability of non-failure operation in contact junctions is constantly growing. There are two reasons – constant thermographical inspection (the longer it has been carried out, the less heating points will be discovered) and reconstruction of substations (thermographical defects in modern electric equipment meet are many times less frequent in comparison with the old equipment).
5. Statistical analysis of discovered defects in electric equipment allows to determine the reliability parameters of this equipment and to find out their specific features, development direction and reason behind the differences.

Conclusions

Infra-red thermography is one of the most convenient and exact methods for analyzing the technical condition of a working electric equipment in the grid.

It is the most quick and safe method for preventing the damages and emergencies of electric equipment.

Thermographic diagnostics does not solve all technical problems of defective electric equipment, but provides timely information on where and when the damage or a more serious damage can occur; i. e. thermographic inspection allows undertaking operative measures for timely repairs or removal of this equipment.

The methods of thermographic diagnostics are widespread in many countries. In Estonia this method of diagnostics has already been used by N. Dorovatovski for the last six years. For example, in 1999 the use of thermal camera in 136 substations of *Eesti Energia* Ltd. National Grid enabled to inspect more than 7,000 electroinstallations, including 70,000 contacts and contact junctions. The obtained results and their analysis have enabled to plan preventive maintenance of electric equipment and running repairs.

The analysis of defects diagnosed in electric equipment shows that the defects are mostly caused by the deficiency of construction, manufacturing and installation, and their physical and moral aging. This is most relevant in Estonia where a large part of equipment is of considerable age, which increases the importance of thermographic diagnostics.

Several detected defects are caused by poor quality of repairs and operation. Thermographic diagnostics enables to define the quality of the repairs and operation of the given electric equipment in order to prevent damages or emergencies. That is why thermographic inspection should be carried out after each repair.

Monitoring of electric equipment in substations with the help of thermal camera allows saving both financial and material resources and increases the reliability of electric equipment. The defects of electric equipment caused by overheatings of its contacts and contact junctions can cost approximately 3.0 million EEK per year. Approximately 60–75% of these defects can be detected with the help of thermographic diagnostics, which leads to saving up to 2.0 million EEK per year.

As a conclusion it is possible to claim that thermographic diagnostics of electric equipment in stations and substations is a very efficient, fast and exact method not causing any damage to the equipment, and that the method has great prospects in the future of electrical engineering.

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