GRAPHICAL MODEL OF IMPERFECTION IDENTIFICATION IN INSTRUMENTAL TRANSFORMERS BY DGA

I.Davidenko
Ural National Technical University, Ekaterinburg, мail box 261, 620057, Russia
Email: jera@r66.ru

Abstract: The paper considers types of imperfections and causes of their initiation and the graphical model of the equipment technical conditions classes description basing on DGA results. Images are given, describing 12 imperfections and perfect state for instrumental transformers (IT) in the form of graphical model, both with the algorithm of their recognition. The model can be applied to diagnostics of the other types of oil-filled equipment

1. INTRODUCTION

Interpretation of DGA results is widely used for early diagnostics of imperfections progressing in power transformers. The process of diagnostics can be divided into 2 steps:

- establishing the existence of progressing imperfection basing on exceeding typical values of gas concentrations (TGK) and velocities of their generation;
- imperfection of identification character.

But criteria of diagnostics of power transformers cannot be duplicated for IT as they have some peculiarities in the causes of imperfection appearance, design (different value of ratios of paper/oil) and conditions of exploitation.

It is quite natural that while accumulating experience in exploitation, diagnostics, repair, and investigation of IT failures widening and improvement of diagnostic criteria for this equipment becomes possible. Precision of diagnostic criteria is one of the determining factors of equipment dependable service, hence the main aim of the given research was determination of IT diagnostic criteria set for both steps of diagnostics.

2. CRITERION OF TYPICAL GAS CONCENTRATIONS

The aim of the first step of diagnostics is to divide IT into two groups of technical conditions classes on the base of DGA results: free of imperfections and with progressing imperfection. Calculation of TGK criterion for IT is based on accumulated DGA data processing with methods of mathematical statistics according to the procedure worked out by the author [1]. The research became possible thanks to information accumulated in the database of expert-diagnostic system “Albatros” (EDIS “Albatros”) during 18 years of its exploitation at power companies of Russia, Moldavia, Ukraine, and Latvia (more than 123 enterprises, more than 200 workplaces) and to experience of such research. Calculations were based on the data selected at the enterprises with considerable volumes of DGA results accumulated during exploitation, with reasonable confidence to this information which depends both on the quality of operation organization, staff qualification, and on the perfection of the applied methods and instrumentation. Total samples capacity was more than 5000 DGA results.

To make TGK criterion describing up state of IT more precise it was necessary to begin with determination of design and regime features of IT for their differentiation. For this aim dependences of TGK values on the following factors have been investigated:

- oil protection type (hermetic, leaky);
- oil grade;
- equipment function (current and power IT);
- operation period;
- power class;
- type of solid insulation (paper-oil or paper-oil of condenser type).

Using dispersion analysis according to criteria Fisher-Snedecorn factors significance was determined for ones influencing TGK values and their effect degree. As a result according to design features IT have been divided into 9 groups. In its turn each of the groups was divided into 4 operation periods. Factors influencing TGK values were ranged according to the effect degree as follows: equipment function, oil protection type, oil grade, operation period. Oil grades are divided into three groups depending on the content of aromatic hydrocarbons as this index is connected with gassing ability and oil oxidation rate:

- GK with minimal content of C_A=1,6-3%;
- TKp with maximal content of C_A up to 30%;
- the other oil grades with C_A=9-18%.

The effect of power class was revealed only for one type of current transformers (CT). It may be explained by the fact that some IT of higher power classes physically consist of elements of low power classes. TGK values were determined according to the found effect factors via integral distribution function of gas concentrations for IT in operation. The level of TGK determination was selected taking into consideration values of damageability flow:

- for voltage transformers 110-500 kV – 97%,
- for CT 220-750 kV – 95%,
- for CT 110 kV – 97,5%.

Table 1 contains TGK values obtained for operation period following the break-in one.

Table 1: Typical gas concentrations of instrumental transformers.

Solid insulation type	Power class, kV	Oil protection type	Oil grade	Typical gas concentrations, ppm						
				H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2
Current transformers										
Paper-oil of condenser type	330-750	Film	GK	30	12	20	13	2	600	1200
			***	13	8	21	5	2	800	1700
		Free breath	TKp	13	6	23	5	2	380	1100
Paper-oil	110	Free breath	GK	2800	1300	6	100	2	70	850
			***	1600	1200	5	450	2	130	1150
			TKp	1400	830	5	340	2	147	1540
	220-500		***	23	9	15	72	2	670	1000
Voltage transformers										
Paper-oil	110-500	Free breath	GK	23	10	9	8	2	100	1100
			TKp	12	7	7	9	2	120	1800

*** - the other oil grades with C_A=9-18%

If concentration of one or several gases for IT under diagnostic exceeds values given in Table 1 one must make sure that this excess is connected with progressing imperfection and is not produced by other reasons.

For this aim rates of concentration growth are compared with their typical values. For IT dangerous rate of gas concentration growth differs from the one stated for power transformers because of the less oil volume and oil circulation absence [2]. If gas concentration growth is fixed then one must pass to imperfection identification step.

3. IT IMPERFECTIONS IDENTIFICATION BASED ON DGA RESULTS

Appearance of gases in IT oil can be the effect of insulation destruction as a result of local abnormal energy liberation due to:

- production technological irregularity, including wire-edge formation of metallic parts, solid insulation defects, insulation heterogeneity, underimpregnation, assembling leakage, sealing unit defect, contact loss in current-carrying circuit;
- external factors influence, including prolonged voltage increase, overvoltage (high-frequency), storm, open-phase operating conditions, ferroresonance, current overcharge, electrodynamic effects of currents of close shot circuits;
- operational factors, such as insulation wetting, rubber seal displacement, oil level lowering, oil characteristics worsening, mechanical dirt presence, insulation contamination, contact loss;
- aging processes due to electric field intensity, temperature, time, catalysts influence, and etc. on insulation, that is, cellulose degradation, oil decomposition products formation and deposit.

To obtain criteria of identification of IT imperfections basing on DGA results database have been collected including 107 cases of equipment unsealing. The most of the data were collected by the designers of EDIS ”Albatros” at the enterprises where it was applied. In all the cases we have got reliable descriptions of unsealing results, DGA and other measurements results which were made before unsealing.
After studying the causes of IT damageability, incidents and IT unsealing during their repair, taking into account IT design and operation experience, dictionary of IT imperfections has been compiled. Then basing on manifestations of imperfection traces for the collected cases and on analysis of their origin causes and DGA results 9 imperfections have been selected for CT and 3 imperfections - for voltage transformers (VT). Table 2 contains description of IT technical condition classes, based on manifestations of imperfection traces revealed during their unsealing, and their origin causes.

To get imperfection identification criteria all the cases of IT unsealing have been analysed by experts and were attributed to technical conditions classes according to Table 2. Then program unit selected from the collected data samples on definite imperfection and synthesized imperfection description for each sample in the form of graphical image coordinates, using the method worked out by the author. The results of the synthesis and algorithm of imperfection identification are given below.

It is offered that an object state is mapped in the form of 8-ray diagram based on DGA results.

Table 2: Imperfections (technical conditions classes) for instrumental transformers.

Fault type	Problems founds	Description of imperfection type based on unsealing case
	Current transformers	
Low energy PD, aging	Rough edges of metal units, insufficient impregnation of insulation with oil due to incorrect storage or manufacturing.	Fragility and darkening of paper, oil. Sludge.
High energy PD and thermal fault of low temperature	Commutation effects. Overvoltage. Presence of mechanical dirt, paper fiber, gases. Jags of metal parts. Incorrect contact in low voltage circuit. Initial stage of wetting. Disturbances in the circuit of equalizing potential	Point disruptions in some layers of paper insulation. Oil pollution and color change. Soot particles dredge in oil. Contact loss points pitting.
PD and thermal fault of low temperature (X-wax)	Oil defect, low loading (temperature), commutation effects, overvoltage. Insulation heterogeneity.	X-wax between insulation layers. Traces of branchy discharge between paper layers.
High energy PD	Insufficient impregnation and wetting of solid insulation. Oil wetting, presence of mechanical dirt, paper fiber, gases in it. Jags of metal parts.	Point disruptions in some layers of paper insulation. Carbon tracking at armatures edges.
Thermal dielectric breakdown	«Triangle» poor insulation. Increased local electric field intensity due to manufacturing shortcomings: cavity presence, insufficient impregnation of insulation with oil**.** Electrodynamic effects of through currents of close shot circuits. Paper folds. Insulation wetting. Substantial materials aging accompanied with insulation dielectric overheating or heating with nominal current and external heat imposition (summer, solar radiation)	Several punched paper layers, carbonized charge channel is seen.
Low energy PD and thermal fault of high temperature	Contact and insulation integrity loss brek in high voltage and earth circuits and circuits between units.	Changing of color of paper insulation its destruction because of depolymerization
Ionization dielectric breakdown	High moisture and gas content in oil and insulation. High-frequency overvoltage.	Traces of through disruption of inner insulation without carbonized paper edges.
High energy PD and thermal fault of high temperature	Wetting and aging of insulation, cracks on cover porcelain or electrical field heterogeneity, deposition forming and its wetting. Oil level lowering up to denudation of upper part of the tore at sharp temperature decreasing. Poor contact in high voltage circuit.	Temper colors and arcing traces on current - carrying conductors, black carbon impregnations and insulation destruction. Carbonized paths.
High energy discharges (arcing)	Fault, break of current-carrying circuits. Fault of potential equalizing circuit.	Temper colors and arcing traces on current - carrying conductors.
	Voltage transformers	
High energy discharges accompanied with thermal fault of high temperature	Short circuit in high and low voltage circuits due to overvoltage, insulation wetting, insulation pollution, etc. Contact fault or break in high voltage circuits, instrumental outlet, screen.	Equalizing winding pitting, pitting of part of windings of high and low voltage.
Thermal fault of high temperature, insulation aging	Overload of high a voltage winding. Open-phase mode. Voltage prolonged increase. Reducing of secondary circuits insulation. Poor contact. Defect of magnetic conductor. Oil and paper aging.	High and low voltage winding insulation carbonization. Carbon presence. Oil color change, sludge.
Thermal fault of high temperature due to ferroresonance	Ferroresonance phenomena in power grid point.	Paper destruction. High voltage winding insulation carbonization. Oil color change.

At this diagram gas concentration values are located along 7 rays, and the sum of these values is calculated by formula (1) located along the 8-th ray (Fig.1):

$$S = \sum_{n=1}^{5} K_i + m * (K_{CO} + K_{CO2}) \qquad (1)$$

Where: K_i = values of concentrations of hydrocarbon gases and hydrogen (ppm);
K_{CO} , K_{CO2} = values of concentrations of carbon monoxide and dioxide (ppm);
m = scaling factor equal to 0,01 for CT and 0,005 for VT.

So concentrations of carbon monoxide and dioxide are mapped in less scale than concentrations of other gases including gases sum. Concentrations are laid off from the circle which depicts boundary of gases revealing with instrumentation. For convenience this boundary is accepted to be equal to 2 ppm for all the gases. The obtained points of neighboring rays are connected with line segments. As a result one gets the image of the object being diagnosticated.

At the first step of diagnostic the image of the object being diagnosticated and TGK image in absolute DGA values, corresponding to it, are built in ray diagram. Necessary TGK values are selected depending on equipment design philosophy and operation period (table 1). TGK values can be considered as an image of equipment defect-free conditions. It is shown as dash line in Fig.1. If image describing an object being diagnosticated leaves the domain limited with TGK image at least for one of gases then availability of progressing imperfection is supposed. Having verified that the velocity of one of gases is higher than its normal value and thereby confirming availability of progressing imperfection in equipment, we pass to the second step of diagnostics – imperfection identification.

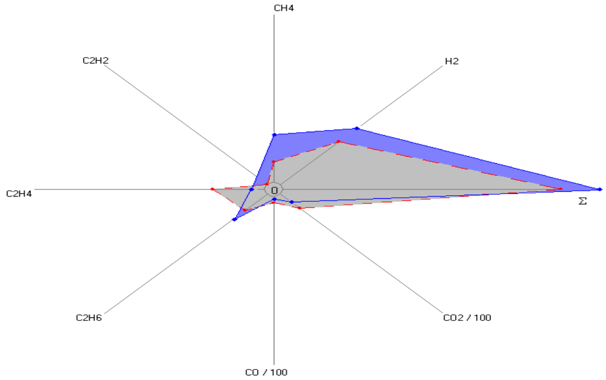

Figure 1: Images of the object under diagnostics and of defect-free state of equipment

Imperfection images are saved in the form of relative values of gases content normalized by weighted sum of seven gases concentrations where gases sum always equals to 1. To map imperfection images in the diagram they are scaled such a way that points of imperfections and of the state being identified are matched along the ray on which gases sum is depicted. Then imperfection recognition is conducted by calculating —proximity measure by mean-square criteria, weighted in accordance to imperfections images by the formula:

$$F_n = \sqrt{\sum_{i=1}^{7} h_{ni} * (K_i - K_{ni})^2} \quad (2)$$

Where: n = imperfection number

K_i = coordinate of image describing object being diagnosticated, that corresponds to *i-th* gas

K_{ni} = coordinate of image of *n-th* imperfection to *i-th* gas

h_{ni} = weighting coefficient taking in account informativity of *i-th* gas for *n-th* imperfection.

The 8-th coordinate of image (gases sum) is not included in the formula as after scaling the images $K_8 = K_{n8}$ and their difference equals to zero. Minimal value F_n will denote the imperfection in the object being diagnosticated.

Procedure of imperfection identification can be supplemented with application of coefficients of danger and failure probability [3]. If situation of «the same similar» images of imperfection arises in recognition then imperfection with maximal coefficient of danger is selected to minimize hazard of risk of erroneous recognition. If ambiguity of imperfection recognition still remains then we select the most likely imperfection among «similar and with the same degree of danger» ones. Values of coefficients of danger were defined basing on expert estimates. Values of coefficients of probability were calculated on the basis of statistics of IT damageability. Surely, the suggested approach is more convenient if it is realized in software such as EDIS «Albatros».

Fig. 2-10 show images of imperfections for CT, and fig. 11-13 – for VT.

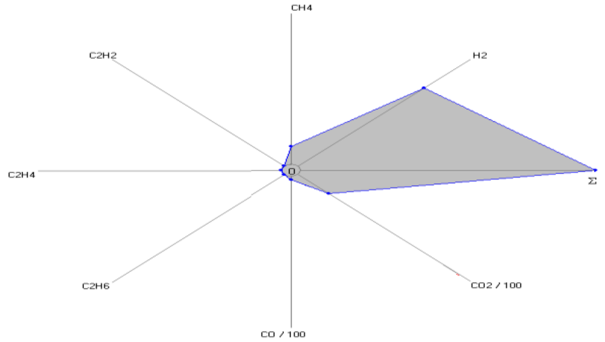

Figure 2: Low energy PD, aging.

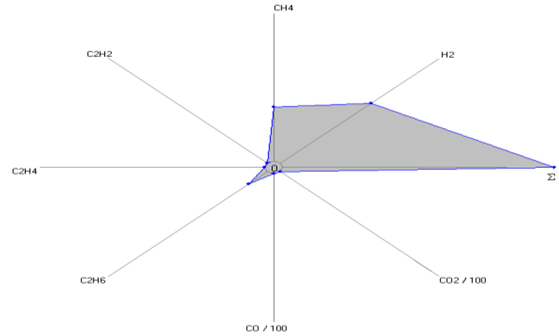

Figure 3: High energy PD and thermal fault of low temperature.

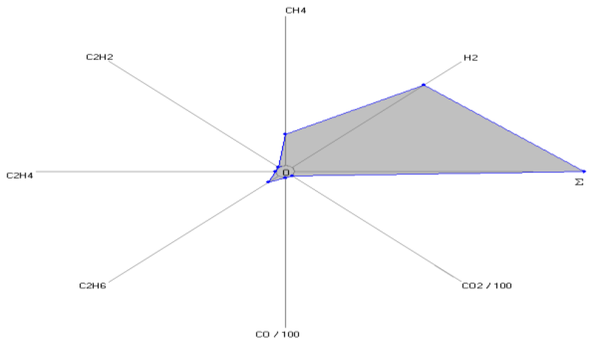

Figure 4: PD and thermal fault of low temperature (X-wax).

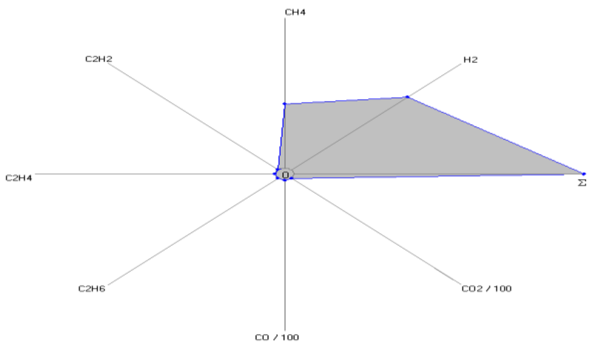

Figure 5: High energy PD.

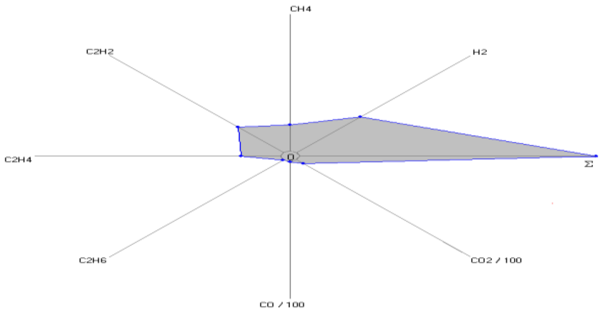

Figure 6: Thermal dielectric breakdown.

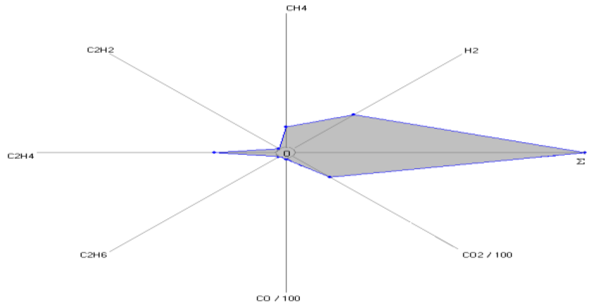

Figure 7: Low energy PD and thermal fault of high temperature.

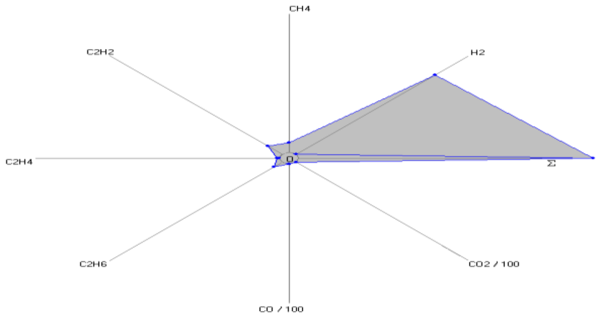

Figure 8: Ionization dielectric breakdown.

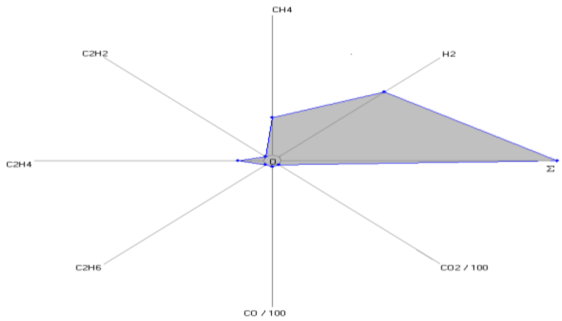

Figure 9: High energy PD and thermal fault of high temperature.

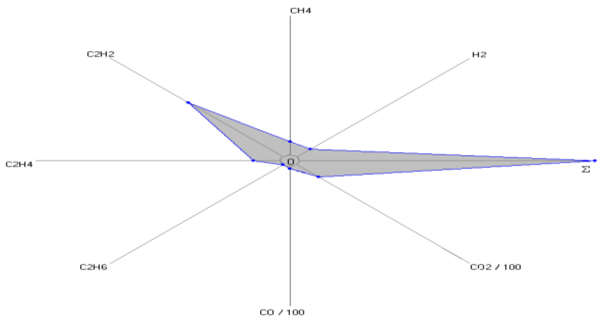

Figure 10: High energy discharges (arcing).

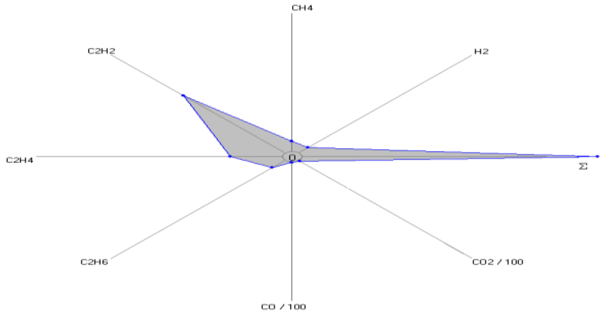

Figure11: High energy discharges accompanied with thermal fault of high temperature.

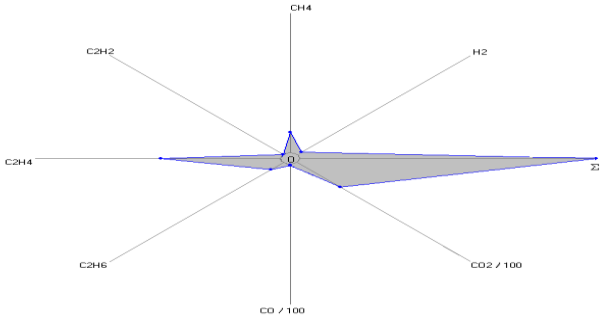

Figure 12: Thermal fault of high temperature, insulation aging.

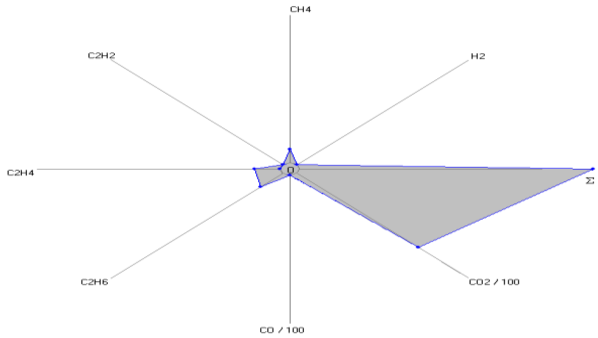

Figure 13: Thermal fault of high temperature due to ferroresonance.

4. MULTIASPECT APPROACH TO IT DIAGNOSTIC AND IT RANGING BY TECHNICAL CONDITIONS

The experience of the author of the paper and creators of knowledge base EDIS «Albatros» suggests that in addition to imperfection identification based on DGA it is necessary to apply diagnostic features which allow to identify processing imperfections on the base of other types of measurements. Obviously none of such measurements as insulation characteristics measurements, oil physicochemical analysis, thermal imaging control and winging resistance measurement, etc. can provide the same wide palette of imperfection recognition as DGA (see Table 2). Being early diagnostic of processing imperfections, DGA gives the opportunity to have timely frequency control of IT. But conclusion on imperfection type is recommended to be done if diagnostic features of at least two kinds of measurements point it out.

For example, CT state presented at Fig.1 is identified as «High energy PD and thermal fault of low temperature» and is rather characteristic case of damage. There can be different causes of this state thus it is necessary to conduct additional measurements to reveal the real reason. Both measurement of winging resistance and thermal imaging control can point at poor contact in winging circuit. The increase of dielectric loss tangent of insulation with growth of measurement voltage can point at X-wax formation. Joint analysis of DGA and results of the other kinds of measurements can help in prognosis of imperfection character and danger and in planning additional measurements for its specification and revealing the cause of its rise.

Application of several kinds of measurements for analysis will allow specification of the cause of imperfection progressing which is necessary for correct planning subsequent actions of staff on IT operation or repair.

Taking into account chains development of on type of imperfection into another, stages of imperfection (danger) processing and causes of its initiation rise, IT can be ranged by their state and operations of their repair or replacement can be conducted in time. For example, the following chains of imperfection processing can be:

- winging displacement and insulation homogeneity disturbance due to electrodynamic influence can bring to strong PD arise, with time converting to discharges terminating with thermal breakdown;
- formation and accumulation of X-wax as aging product, accompanied with PD strengthening – thermal breakdown of solid insulation;
- discharge initiation due to insulation wetting (at first it can be oil wetting and then solid insulation wetting) – solid insulation breakdown.

When ranging IT, it is necessary to take into account time of imperfection processing and its danger. For example, formation of deposition connected with aging proceeds slowly (for years), but discharge development between paper layers takes months or even days, and thermal breakdown heat disruption of solid insulation can carry during several hours. At the first step of ranging IT are divided into groups basing on velocity of imperfection processing: high, medium, low. Then IT with dangerous and quick-progressing imperfections must be attributed to the group of equipment that is to be immediately removed of operation. Besides, we must consider during ranging if changes in technical characteristics, connected with the supposed imperfection, are of reversible or nonreversible character. In many cases IT life time can be prolonged by: insulation drying, oil properties recovery, measuring terminal contacts and insulation reconstruction, etc. Hence in further ranging IT are divided into groups subjected and not subjected to repair. At the same time the questions of economical advisability of such repair must be considered basing on local conditions.

5. CONCLUSION

The suggested method of imperfections identification with the new graphical model obtains wider possibilities on precision and range of recognised imperfections, excludes unrecognizable states of object, obtains clearness, allows using creative thinking of the person, and hence make the process of information analysis more efficient.

IT DGA gives the opportunity to determine an imperfection at its early stage of development, in proper time put an object to frequency control and conduct additional necessary measurements. Such actions prevent serious nonreversible damage of IT itself and the connected equipment. Imperfection identification basing on several kinds of measurements allows IT diagnostics with higher reliability and wide range of technical conditions recognizable classes. The approach of multiple-aspect estimate of IT conditions recommended in the paper can be used for IT ranging according to their technical conditions for the following exploitation, replacement or repair.

6. REFERENCES

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[3] I. V. Davidenko, “Patent № 2008106459 from 19.12.2008 for useful model System of diagnostics of oil-filled instrument transformers”, Federal service on intellectual property, patents and trade marks, FIPS Rospatent.