**Milan Belik[1], Oleksandr Rubanenko [2], Olena Rubanenko[1,2,3]**

University of West Bohemia, Pilsen, Czech Republic (1)
Vinnitsya National Technical University, Vinnitsya, Ukraine (2)
Institute of Renewable Energy of NAS of Ukraine, Kyiv, Ukraine (3)

doi:10.15199/48.2023.11.31

# Prerequisites for the creation of Digital Twin in the tasks of determining the technical condition of power transformers in specific operating conditions

***Abstract**. The paper proposes an analysis of the technical conditions of power transformer operation. The time for repairing the power transformer was presented depending on capacity. The proposed classification of the direct and frequent damage to power transformers. The results of damages to power transformers in Ukraine and abroad were analyzed. The manuscript consists of the following parts: introduction; damage analysis of transformers; Digital Twin for determination of technical condition power transformer and usage neuro-fuzzy modeling in MATLAB to defind index residual resource of the power transformer.*

***Streszczenie.** W artykule zaproponowano analizę warunków technicznych eksploatacji transformatora elektroenergetycznego. Przedstawiono czas naprawy transformatora mocy w zależności od mocy. Proponowana klasyfikacja bezpośrednich i częstych uszkodzeń transformatorów elektroenergetycznych. Przeanalizowano skutki uszkodzeń transformatorów mocy na Ukrainie i za granicą. Rękopis składa się z następujących części: wstępu; analiza uszkodzeń transformatorów; Cyfrowy bliźniak do określania stanu technicznego transformatora mocy oraz wykorzystanie modelowania neuro-rozmytego w MATLAB-ie do wyznaczania indeksowego zasobu szczątkowego transformatora mocy. (**Przesłanki do stworzenia Cyfrowego Bliźniaka w zadaniach określania stanu technicznego transformatorów elektroenergetycznych w określonych warunkach eksploatacji**)*

**Keywords:** transformer, technical condition, no-load autotransformer, resonant frequency.
**Słowa kluczowe:** przepięcia rezonansowe, tryb niesinusoidalny, autotransformator bez obciążenia, częstotliwość rezonansowa..

## Introduction

Nowadays, there is a large number of high-voltage power transformers (PT) in operation:

- block at power stations,
- own needs at power stations and substations,
- communication autotransformers at power stations and substations,
- step-down PTs at substations of enterprises of electric distribution networks.

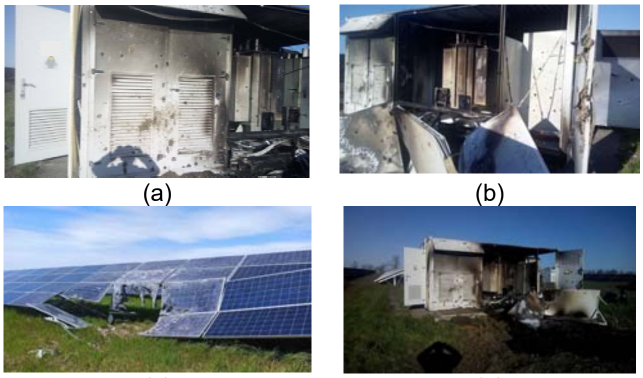
The reliability of the power supply, the quality of electric energy, the cost-effectiveness of the process of its transportation and distribution, etc., depending on the proper operation of power transformers.

Unfortunately, a sign of the present is that the aggressor state, to expand its territories at the expense of other states, started a war. Critical infrastructure, namely the energy sector, is destroyed during the war. Power transformers are damaged at stations and substations (Fig. 1 [1]). Domestic enterprises - manufacturers of PTs are partially damaged or have reduced production.

Fig. 1. Damaged power transformer at high-voltage substation.

Equipment renewable energy sources exactly photovoltaic power plants also were damaged. The main damages receive photovoltaic panels, inverters, control boxes, and power transformers (Fig. 2).

In [2] noted, that before the war more than 40 % of distribution electric networks PTs have worked for more than 30 years, which exceeds their passport life (25 years). So, situation just start more worth



(a) (b) (c) (d)

Fig. 2 Damaged equipment of the photovoltaic power plants: damaged control box; (b) and (d) destroyed power transformers; (c) destroyed photovoltaic modules.

The previously created PT reserve of operating enterprises has been exhausted or has decreased. Considering the difficulties with the transportation of new PTs to the place of operation, the issue of logistics in military operations is acute.

In ensuring a reliable and high-quality power supply, the availability of transformers is another problem that enterprises of electric distribution networks, or other large enterprises that operate transformers, face today. In the conditions of full-scale war, due to damage to power transformers, due to disruptions in supply chains, the electric power industry is witnessing the problem of purchasing replacements for various damaged electrical equipment, and transformers have become a particular type of equipment that cannot be purchased in a short time.

For example, about 90% of the consumed power in the USA is transmitted through powerful transformers. Due to the shortage of domestic manufacturers (in wartime conditions), most power transformers are imported, which creates a potential bottleneck in the power supply system. Power supply enterprises are now faced with the problem of developing strategies for using backup ways to ensure the necessary power supply, including longer operating time of transformers in overload mode and storage of spare new or repaired transformers at the enterprise.

There are also complex logistics issues during the delivery of powerful power transformers from other countries to the place of operation in the conditions of military operations on the territory of Ukraine. Therefore, transformer replacement schedules and logistics must be efficiently and effectively planned. Fig. 3 shows the transportation of a power transformer for commissioning at a power station.

(a) (b)

Fig.3. Transportation of a power transformer for commissioning at a power plant in wartime conditions in Ukraine.

Fig. 4 shows the percentage value of transformers exported by the USA depending on their capacity.

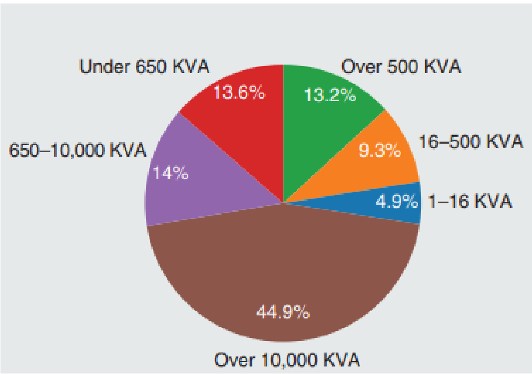



Fig. 4. The global transformer trade average export value by power rating capability. (Source: Office of Technology Evaluation.)

The demand for powerful transformers determines their production and indirectly affects the reliability of power systems. Power supply companies must have their model for determining the technical condition based on tests and results of monitoring/measurement of diagnostic parameters of power transformers (PT). You must create a reliable "backup transformer" strategy to do this.

It is also necessary to develop a strategy for monitoring the technical condition of power transformers using a multifactorial analysis. This is caused by the need to rank PTs by the place of their installation and replacement, by the need for priority replacement, and by the logistics of PT delivery to the location of further operation [3].

In the conditions of the war, there are many repaired PTs in operation or PTs whose resource has been significantly reduced. In the conditions of possible long-term overloads of such outdated and repaired transformers, it is essential to transition electrical industry enterprises to operation when determining the predictive technical condition of power transformers has an advantage in the requirements of the influence of an existing malfunction on the technical condition of the transformer, or the needs of impact on the consequences of the destruction of both the transformer and related electrical equipment.

Therefore, power supply interruptions can be reduced by reserving power transmission paths or overloading the PT for a sufficient time.The permissible overload time changes continuously and depends on many factors: weather conditions, electricity generation, and consumption, the technical condition of the substation, etc. Therefore, a periodic and permanent control of the technical state of ST is essential.

Calculation of the load capacity of the transformer. Therefore, it is essential to determine and take into account the load capacity of the transformer both during the predicted short-term overload of the PT, in the conditions of short-term repair of damaged adjacent equipment, and the possibility of long-term overload of the PT in the long-term post-emergency mode of operation of the power system.

In this case, it is necessary to rank the PTs according to their overloading (loading) capacity to use them optimally in terms of reliability in the post-emergency mode of operation of the power system.

The most often used is the 24-hour forecast ranking of PT by load capacity. However, scale practices vary from country to country and organization. Sometimes, when rating transformers, ambient temperatures are taken into account. Determination of the predictive value of the load capacity of the PT is sometimes carried out for less than 24 hours (sometimes for the nearest 15 minutes to even 4 hours in the post-emergency mode of the power system). This is the ranking of the power system by load capacity in the so-called short-term special or post-emergency mode of the power system:

- STE ranking (short-term emergency). There is a ranking of PTs during their more extended operation in a special mode of power system
- LTE (long-term emergency) ranking. Uptime during LTE is longer than STE but less than 24 hours. In the post-emergency mode of the power system, it is possible to operate the PT with an overload. During the operation of the PT, damage to the PT occurs, or deterioration of the technical condition of the nodes and parts of the PT, which significantly limits the possible time of overloading of the PT in the post-accident modes of the power system (possible in the conditions of military operations).

The goal of the paper is to research the prerequisites of developing DT for PT in the current conditions of the operation of Ukraine's power system.

**Damage analysis of transformers.**

A power transformer consists of many components and parts. Their failures in the operation process affect its efficiency and, therefore, the reliability and quality of the operation of the electric power system. The results of studies of literary sources indicate that, both in Ukraine and abroad (Table 1), damage to PT nodes and parts is caused by damage to windings and magnetic wires. This proves the need to consider the condition of these elements of the transformer during its operation.

Table 1. Distribution of transformer nodes according to their damage

| Malfunctions | Ukraine | Germany |
|---|---|---|
| Tank | 7.6 % | 3.6 % |
| Regulator under load | 9.5 % | 33.9 % |
| Winding | 9.7 % | 32.1 % |
| Magnetic Core | 5.4 % | 7.1 % |
| Cooling system | 23.1 % | 0.9 % |
| Transformer bushing | 15.6 % | 11.6 % |
| Insulation | 29.1 % | 9.8 % |
| Tank | 7.6 % | 3.6 % |

The direct and frequent damage to power transformers can be divided into the following [7-12]:

a) insulation damage:
- deterioration of oil quality;
- the sharp drop in oil level;
- abnormal increase in oil temperature and local overheating;
- defects of inter-sheet (paper) insulation.

b) damage to inputs:
- a breakdown of the body;
- shorting the inputs of different phases with each other;
- leakage of the housing;
- low-quality reinforcement;
- heating of porcelain;
- heating of the steel flange.

c) winding damage:
- twist circuit;
- broken windings;
- a breakdown of the body;
- interphase short circuit;
- shorting of parallel wires in turns of the helical winding at the place of transposition;
- breakage of one or more parallel wires in the winding;
- radial deformation of turns.

d) damage to the magnetic circuit:
- local shorting of charged steel plates and "fire in steel";
- local damage to the insulation of the steel plates, which causes the closing of the steel plates;
- increased vibration;
- grounding break.

e) damage to the tap-changer:
- melting or burning of contact surfaces;
- overlapping between phases or separate branches (the defect is similar to an interphase short circuit of the windings).

f) damage to the cooling system:
- mechanical deformation of the radiator;
- circulation pump failure;
- failure of the forced-blowing system.

g) tank damage:
- leakage into the transformer tank (leakage);
- oil leakage at joints;
- mechanical damage.

Some of the reasons for PT damage are shown in Fig. 5.

Study of the repair time of PT. Considering the value and importance of PT for electric power enterprises and analyzing the damage and reasons that led to the removal of PT from the operation, it is necessary to remember the time spent on the repair or replacement of PT because economic costs and social problems depend on it.

More often than not, the PT cannot be repaired, which indicates severe damage that led to its loss.

The second position is the repair carried out by specialized technical services in their workshops. However, here it must be taken into account that the company also incurs economic costs during such repair because it is the delivery of the PT from its operation to the location of repair and back, diagnosis, disassembly, and collection of PT, drying, etc. Determining the time of repair of PT damage in Ukraine after war attacks is presented in Fig. 6.

The repair time of the PT depends on its technical condition, which is determined by methods and means of diagnosis. Today, there are many methods and tools for diagnosing power transformers, such as, for example, thermal imaging control, chromatographic analysis of dissolved gases in transformer oil, and others.

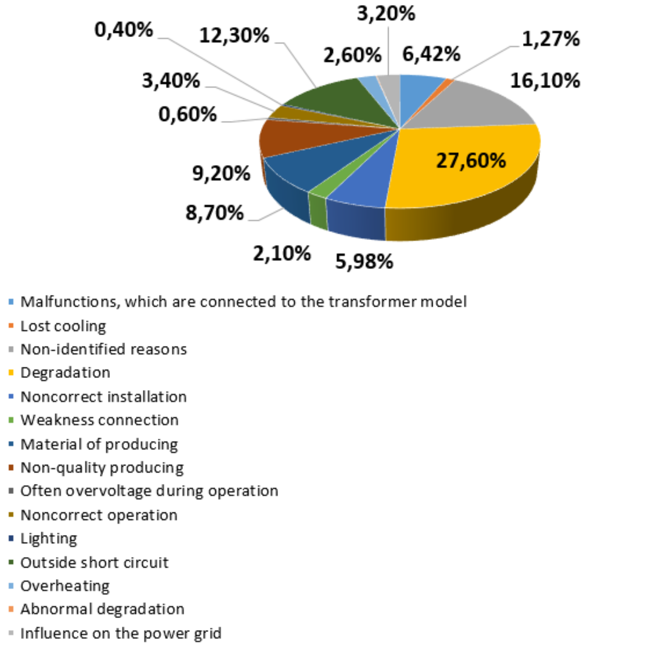



Fig. 5. Results of damage analysis of ST a) in Ukraine and b) abroad.

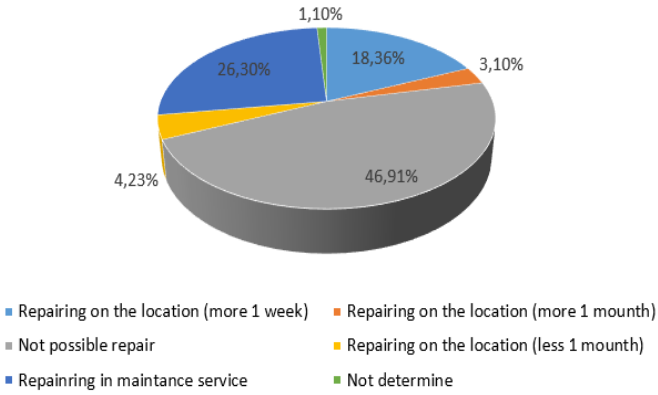



Fig. 6. Determining the time of repair of ST damage in Ukraine after war attacks.

PT status control is determined by its maintenance strategy. As a rule, a system of decommissioning based on damage is applied to low-capacity PTs. For large-capacity PTs, an approach based on the schedule of inspections and repairs is used according to the established plan. However, it is worth noting that in some cases, such a strategy is economically impractical since maintenance according to the planned schedule involves actions that may not be appropriate for a specific PT, as well as the removal of an PT due to damage can lead to the complete loss of such equipment. Therefore, today, methods of monitoring the technical condition are used, which are divided into two categories - with periodic and permanent methods of diagnosing parameters. Nowadays, complex ways of determining the technical condition of the transformer are popular, as they allow you to objectively assess the condition and identify defects in all parts of the transformer, in particular in the active part (windings and magnetic core), inputs, cooling system, voltage regulation system, etc. Complex diagnosis of PT covers the stages: analysis of characteristic defects of this type of transformer; analysis of technical documentation and results of current operational measurements; carrying out measures on a working transformer in load and idle mode, as well as on a disconnected transformer; oil sampling from the tank, inputs (oil-filled), transformer voltage regulation contactor (regulator under load) and carrying out physical and chemical analyzes of oil in the laboratory.

Several standard measurements and tests of PTs during acceptance and operational tests are known:

- measurement of winding insulation resistance;
- measurement of the tangent angle of dielectric losses and capacitance;
- measuring the resistance of DC windings;
- measurement of short-circuit resistance;
- measurement of current and XX losses at reduced voltage;
- measurement of oil characteristics;
- measurement of frequency characteristics.

Frequency analysis methods involve the analysis of the amplitude values of the response signal to the test signal applied to the ST windings. They are currently used to determine their technical condition. This method consists in first measuring the amplitude values of the voltage (the parameter may be different) of the response signal to the test signal and the voltage of the test signal. Next, the transmission coefficient of the test signal at a different frequency (the value of the transfer function) is determined as the result of dividing the amplitude value of the voltage (the response signal to the test signal for the current frequency of this signal) by the amplitude value of the voltage (the test signal for the same frequency). This result is often recorded in decibels. Then it is determined by the formula, which is the transfer function of the test signal.

The conducted analysis showed that there are many methods for determining the technical condition of ST. However, despite such a variety of diagnostic techniques and tools, the study of ST damage shows that by controlling only one parameter, it is difficult to detect defects, especially at an early stage of their development. Therefore, it is necessary to use additional diagnostic parameters, for example, transfer function of the test signal, dependence of the residual resistance of the test signal on the frequency, deviation of the initial graph of the support of the phase test signal on the frequency for the current and penultimate measurements.

For this, it is necessary to use additional diagnostic parameters, for example, transfer function of the test signal, dependence of the residual resistance of the test signal on the frequency, deviation of the initial graph of the dependence of the phase test signal on the frequency for the current and penultimate measurements.

In the conditions of low reliability of the unified energy system of Ukraine, it is essential to note that we have a large number of damaged PTs. As a result, the system works with a limited number of PTs, leading to more frequent cases when PTs work in overloaded conditions. These transformers require increased control regarding their insulation characteristics and operating temperature conditions. The operation of PTs in an overloaded state significantly reduces their residual resource, while it is necessary to make every effort to avoid emergency shutdowns.

This problem can be solved with the help of constant online monitoring of the PT, which is based on obtaining data on insulation characteristics based on measured physical values, physicochemical and chromatographic characteristics of transformer oil, and temperature indicators. Combining all these indicators in one software will allow for real-time. Digital Twin technology can implement for this.

**Digital Twin for determination of technical condition power transformer**

Analyzed data presented in Table. 2, allowed made the conclusion that the main reasons, why transformers are removed out of service are as a result of humidification and contamination of oil, insulation as well as defects of bushings [4-6]. Analyzed transformers are operating on substations in industrial PV power plants also [6]. Author, Justin Tuttle, divided DT into three main types (product, productions, and perfomence), corresponds on technologies and described benefits to everyone. Summarising and classifying his views, give us the possibility to create a flowchart presented on Fig. 7 [11].

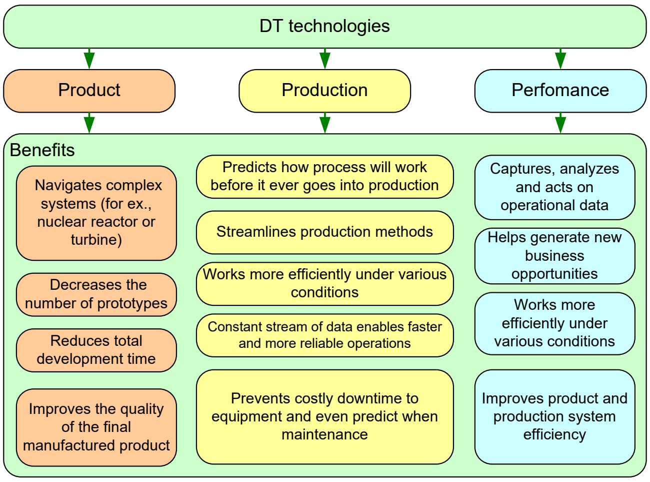



Fig. 7. Technology types DT

Leveraging digital twin technology will help add value, resilience, and efficiency to operating and business models power company. Energy companies will need to innovate their processes or face getting lost in a crowded market. Some big companies already started to create DT in the power engineering sector, included solition for setremining techncial conditon PT, for example, Siemens [11].

One of the issues assessment of technical condition power transformers is the development of the mathematical model. This task is more complex, because some parameters (initial data) haven't been collected, and other parts of the data haven't been measured. So, in this case, it needs to formulate an optimal set of input control parameters. In [7], noted that artificial neural networks (ANN) can help create an online monitoring system for the assessment of the technical condition of the transformers.
Every measured parameter from Table 2 needs to explain in more detail, for example, $Z_k$ is the transformer windings resistance (which possibly obtain just in short–circuit mode); t° is the temperature of connection points; $P_{i.p.}$ is power, that characterizes the quality of magnetic circuit and measured without load; $R_{in}$ is the insulation resistance for revealing the contamination insulation (include oil), for full pictures need to check the dielectric loss tangent, the degree of polymerization and so on); W is isolation moistening; $k_{resid.res.bush.}$ is the bushings residual resource index, measured in relevant units and can have value from 0 up to 1; CADGC is the transformer residual resource index (RRI) by the conclusion of the chromatographic analysis, that assesses oil contamination by the gases; PCA is of the transformer RRI by the conclusions of physical-chemical analyses; CADGd is RRI of the PT by the results of chromatographic analysis of the dissolved hydrogen and acetylene in the oil of the tank and LTC of the transformer tap changer in order to reveal the discharge; kLTC is RRI coefficient of the transformer LTC residual

resource; $I_m$ is the current of oil pumps and fans electric motors of the cooling system; $t^{\circ}_{cool}$ is coolers temperature; $k_{resid.res}$ is RRI of the transformer tank, determined by the availability (takes the value «0») or absent of oil leakage (takes the value 1) [13].

Table 2. Classification of diagnostic parametrs PT for creating digital twin.

| PT node | Control par-trs | Parameter name | Parts | % |
|---|---|---|---|---|
| Windings | $Z_k$ | Winding deformation | 8 | 1.6 |
| | $t^o$ | Deterioration of contact joints state | 10 | 2 |
| | $P_{i,p}$ | Idle power that characterizes of the magnetic quality | 15 | 3 |
| Insulation | $R_{in}$ | Contamination of isolation | 65 | 13.4 |
| | W | Humidification of the isolation | 48 | 10 |
| Bushings | $k_{resid.res.bush}$ or $k_{bush}$ | Defects of bushings | 74 | 15.2 |
| Oil | $CADG_c$ | Content of dissolved gases | 71 | 14.6 |
| | PCA | High moisture content and deviations of other parameters of the oil | 43 | 9 |
| | $CADG_d$ | Discharges in oil | 64 | 13.2 |
| LTC | $k_{def.LTC}$ | LTC defects | 45 | 9.3 |
| Cooling system | $I_{motor.}$ or $I_{mt}$ | The current of oil pump drive motor | 14 | 2.9 |
| | $t^o_{cool}$ | Coolers temperature | 16 | 3.3 |
| Tank | $k_{tank}$ | Tank leakage | 12 | 2.5 |
| Total | | | 485 | 100 |

The issue of creating a digital twin power transformer requires developing an adequate mathematical model, which describes all connections and modes. In [7, 8] highlighted the importance of constructing a digital twin of the transformer operation system, and realizing data interaction feedback between the transformer physical system and virtual image system. Authors of the manuscript [9] noted actuality a development of the method for predicting the remaining life of a transformer based on digital twin technology is proposed, exactly, establishing the digital twin of a transformer and adopting a multi-physics coupling method to calculate the change law of the digital twin's winding hot spot temperature parameters under different working conditions and different operating hours. Analyses of all malfunctions PT which were decided in Table 2 allowed create ba lock-scheme of the residual resource index of the PT (Fig. 7). Table 3 under the term the controlled diagnostic parameter we mean the parameter deviation of which from the norm helped to remove the transformer out of service or was taken into account in the process of its removal out of service. In Table 1 the following diagnostic parameters are given: parameters, that characterize the state of the windings, insulation, bushings, oil, LTC, cooling systems, tank [13].

Having analyzed the data of the Table 1 the scheme was created that shows whether dependent or independent is the impact of diagnostic parameters on the index of total residual resource of the transformer (Fig.8).

The graphical interpretation index of residual resource PT is shown in Fig.8 It is a simplified version because it wasnt described the mutual impact of one monitor diagnostic parameter on the other one. The main goal is to find either in the dependent or independent manner how these parameters influence the coefficient of total residual resource of PT.

Also, In Fig.1 over the parameter the percentage amount of revealed faulty transformers by the noted parameter is shown, that is given in percent from the total amount of faulty transformers.

Consecutively denoted blocks with the parameters, deviations of which from the norm helped to remove out-of-service PT. Blocks with the parameters that help to remove PT out of service on condition of simultaneous deviation of these parameters from the norms, that is stipulated by the requirements regarding the reliability of transformers operation are shown in parallel (for instance, currents of electric motors of oil pumps and fans) [13].

.

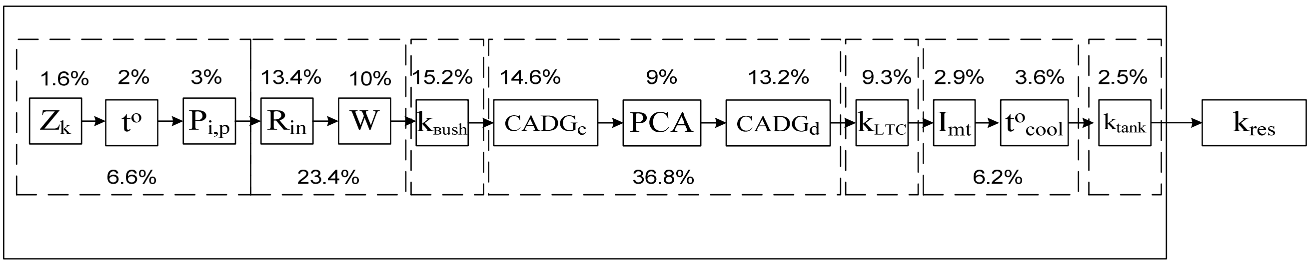



Fig. 8. An example of the wide figure inserted into the text [13]

In order to obtain the generalized index of residual resources of the transformers, suggested passing from the known values of diagnostic parameters (set in named units) to the coefficient of residual resources, corresponding to the values of all diagnostic parameters and the impact of each parameter.

These coefficients are defined in relative units by (1)and that is why they characterize the total output of the transformers from the moment of their technical state control to transition to boundary state which is the residual technical resource(12). Residual resource index by i1th diagnostic parameter:

(1) $$k_{i_1} = \left| \frac{x_{i_1,\lim} - x_{i_1,cur}}{x_{i_1,\lim} - x_{i_1,in}} \right|,$$

(2)

where $x_{i_1,\lim}$ is the admissible limit normative value of $i_i^{1h}$ diagnostic parameter; $x_{i_1,cur}$ is vathe lue of $i_1^{th}$ diagnostic parameter at the moment of control; $x_{i_1 in}$ is initial value of $i_1^{th}$ diagnostic parameter (at the moment of putting into operation of new equipment or after repair), $i_1$ is number of diagnostic pparameters. For serial part of the circuit (Fig1) the coefficient of total residual resource is found by the equation:

$$k_{tot.resid.res.} = \prod_{\tau=1}^{\nu} k_\tau^{p_\tau} \tag{3}$$

where $k_\tau$ is the coefficient of residual resource of PT by $\tau^{th}$ diagnostic parameter; $\tau$ is □$^{th}$ diagnostic parameter; □ is the amount of blocks in the serial part of the circuit of Fig.1, $p_\tau$probability of control parameters deviation from maximum permissible normalized value of this parameter is found by means of expression (3):

$$p_\tau = \frac{y_\tau}{m_2}, \tag{4}$$

where y□ is a number of controlled parameter deviations from admissible limiting normalized value of this parameter, which were revealed by means of $\tau^{th}$ diagnostic parameter control (□ for the serial part of the circuit) from the total number of the revealed deviations of controlled parameters from admissible limiting normalized value; $m_2$ is total ammoun of the revealed deviations of controlled diagnostic parameter from their admissible limiting normalized values.

The For parallel part of the, circuit the coefficient of total residual resource is found by the expression

$$k_{tot.resid.res.} = 1 - \sum_{j=1}^{m_1} \left[ \left(1 - k_{res,j}\right) p_j \right]; \tag{5}$$

where $k_{res,j}$ is the coefficient of residual resource of PT by $j^{th}$ diagnostic parameter; j is number of $j^{th}$ diagnostic parameter; $m_1$ is a quantity of blocks(parameters) in parallel part of the circuit that is reduced. The coefficient of total residual resource of PT is determined by the expression:

$$k_{res} = k_{wind.} \cdot k_{in.} \cdot k_{bush} \cdot k_{oil} \cdot k_{LTC} \cdot k_{cool} \cdot k_{tank} \tag{6}$$

where $k_{wind}$, $k_{in}$, $k_{bush}$, $k_{oil}$, $k_{LIC}$, $k_{cool}$, $k_{tank}$ are determined at the moment of calculation values of the index of residual resource by the elements of the transformer, correspondingly.

**ANN model IRR PT**

In order to develop a ANN model of the PT RRI, the parameters were used, and by each of them the conclusion, regarding the transformer state could be made. For the study of the mathematical model of RRI PT parameters were observed, by each of these parameters the conclusion regarding the condition PT can be defined. But none of these parameters completely characterizes the technical condition of the PT, it only shows some degradation of PT. Artificial neural networks (ANN) model of RRI of the PT was developed with the usage of ANFIS MatLab [12]. Using this ANN model, it is possible to edit the already created probabilistic sample of teaching data. These data help to obtain the analytical dependence of RRI of the PT on diagnostic parameters in the form of the polynomial. For seven input parameters of the model, that randomly changed from 0 to 1, the RRI resource of the transformer was determined, where input parameters of the model were reduced to relative units of their deviation from the norm.

The view of the created ANN is presented in Fig.9. For each input variable ANN model RRI PT four terms with Gaussian membership functions [13] (5):

$$k_{res.i_1} = f\,(x_{i_1}; \sigma_{i_1}; c_{i_1}) = e^{\frac{-(x_{i_1} - c_{i_1})^2}{2 \cdot \sigma_{i_1}{}^2}} \tag{7}$$

where $\delta_{i_1}$ and $c_{i_1}$ are numerical parameter; $\delta_{i_1}^2$ distribution dispersion), and $c_{i_1}$ is mathematic expectation; $i_1$ is ANN input parameter, that corresponds to diagnostic parameter ($i_1$=1, 2, 3, 4, 5, 6, 7), $x_i$ is value of $i_1$ $^{th}$ input parameter of the model: $x_1$ □ $k_{wind}$, $x_2$ □ $k_{in}$, $x_3$ – $k_{bush}$, $x_4$ – $k_{oil}$, $x_5$ – $k_{LTC}$ , $x_6$ □ $k_{cool}$, $x_7$ – $k_{tank}$.

Terms are "normal" values of diagnostic parameter, "minor deviations" of diagnostic parameter value, "prefault" values of diagnostic parameter, "emergency" value of diagnostic parameter.

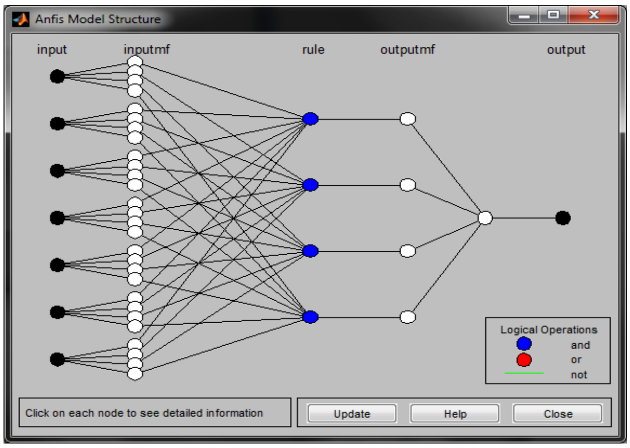



Fig.9 ANN PTin MATLAB

**Mathematical model of total RRI PT can be presented in the system of logic equations.**

$$\begin{cases}
\text{IF}\, k_{wind.} \in \text{"normal"}\, \text{AND}\, k_{in.} \in \text{"normal"}\, \text{AND}\, k_{Bush.} \in \text{"normal"} \\
\text{AND}\, k_{oil} \in \text{"normal"}\, \text{AND}\, k_{LTC} \in \text{"normal"}\, \text{AND}\, k_{cool.} \in \text{"normal"} \\
\text{AND}\, k_{tank} \in \text{"normal"}\, \text{THEN} \\
k_{tot.resid.res} = a_{11} \cdot k_{wind.} + a_{12} \cdot k_{in.} + a_{13} \cdot k_{bush.} + a_{14} \cdot k_{oil} + a_{15} \cdot k_{LTC} + a_{16} \cdot k_{cool.} + a_{17} \cdot k_{tank} + c_1 \\
\text{IF}\, k_{wind} \in \text{"minor deviations}\, \text{AND}\, k_{in} \in \text{"minor deviation"} \\
\text{AND}\, k_{BB} \in \text{"minor deviation"}\, \text{AND}\, k_{oil} \in \text{"minor deviation"} \\
\text{AND}\, k_{LTC} \in \text{"minor deviation"}\, \text{AND}\, k_{cool} \in \text{"minor deviation"} \\
\text{AND}\, k_{tan\,k} \in \text{"minor deviation"}\, \text{THEN} \\
k_{tot.resid.res} = a_{21} \cdot k_{wind.} + a_{22} \cdot k_{in.} + a_{23} \cdot k_{bush.} + a_{24} \cdot k_{oil} + a_{25} \cdot k_{LTC} + a_{26} \cdot k_{cool.} + a_{27} \cdot k_{tank} + c_2 \\
\text{IF}\, k_{wind} \in \text{"prefault"}\, \text{AND}\, k_{in} \in \text{"prefault"}\, \text{AND}\, k_{BB} \in \text{"prefault"} \\
\text{AND}\, k_{oil} \in \text{"prefault"}\, \text{AND}\, k_{LTC} \in \text{"prefault"}\, \text{AND}\, k_{cool} \in \text{"prefault"} \\
\text{AND}\, k_{tan\,k} \in \text{"prefault"}\, \text{THEN} \\
k_{tot.resid.res} = a_{31} \cdot k_{wind.} + a_{32} \cdot k_{in.} + a_{33} \cdot k_{bush.} + a_{34} \cdot k_{oil} + a_{35} \cdot k_{LTC} + a_{36} \cdot k_{cool.} + a_{37} \cdot k_{tank} + c_3 \\
\text{IF}\, k_{wind} \in \text{"emergency"}\, \text{AND}\, k_{in} \in \text{"emergency"}\, \text{AND}\, k_{BB} \in \text{"emergency"}\, \text{AND}\, k_{oil} \in \text{"emergency"} \\
\text{AND}\, k_{LTC} \in \text{"emergency"}\, \text{AND}\, k_{cool} \in \text{"emergency"}\, \text{AND}\, k_{tan\,k} \in \text{"emergency"}\ \text{THEN} \\
k_{tot.resid.res} = a_{41} \cdot k_{wind.} + a_{42} \cdot k_{in.} + a_{43} \cdot k_{bush.} + a_{44} \cdot k_{oil} + a_{45} \cdot k_{LTC} + a_{46} \cdot k_{cool.} + a_{47} \cdot k_{tank} + c_4 \\
\ldots
\end{cases} \tag{8}$$

Output of the model total $K_{tot.resid.res.}$ is found as weighted sum of conclusions (8) of rules base written in the form the system of logic equations:

$$k_{tot.resid.res.} = \sum_{j2=1}^{m3} w_{j2} \begin{pmatrix} a_{j2\,1} \cdot k_{wind.} + a_{j2\,2} \cdot k_{in.} + a_{j2\,3} \cdot k_{Bush.} \\ + a_{j2\,4} \cdot k_{oil} + a_{j2\,5} \cdot k_{LTC} + a_{j2\,6} \cdot k_{cool.} + \\ + a_{j2\,7} \cdot k_{tank} + c_{j2} \end{pmatrix}, \tag{9}$$

where $0 \le w_{j_2} \le 1$ is the weight of the $j_2$-th rule.

Taking into account the iterative computation experiments carried out the vector of membership functions parameters is determined in Table. 3.

Table 3. Parameters of membership function

| Parameters | Input parameters of the model | Name of the term | Number of the rule | Parameters of membership function | |
|---|---|---|---|---|---|
| | | | | б | C |
| Winding state | $K_{wind.}$ | Normal | 1 | 0,38 | 0,79 |
| | | Minor deviation | 2 | 0,47 | 0,51 |
| | | Prefault | 3 | 0,49 | 0,56 |
| | | Emergency | 4 | 0,4 | 0,16 |
| Insulation state | $k_{in.}$ | Normal | 1 | 0,36 | 0,86 |
| | | Minor deviation | 2 | 0,46 | 0,61 |
| | | Prefault | 3 | 0,51 | 0,52 |
| | | Emergency | 4 | 0,39 | 0,17 |
| State of BB | $k_{bush.}$ | Normal | 1 | 0,32 | 0,92 |
| | | Minor deviation | 2 | 0,34 | 0,76 |
| | | Prefault | 3 | 0,49 | 0,53 |
| | | Emergency | 4 | 0,40 | 0,19 |
| State of oil | $K_{oil}$ | Normal | 1 | 0,43 | 0,92 |
| | | Minor deviation | 2 | 0,34 | 0,96 |
| | | Prefault | 3 | 0,41 | 0,59 |
| | | Emergency | 4 | 0,40 | 0,20 |
| State LTC | $K_{LTC}$ | Normal | 1 | 0,39 | 0,97 |
| | | Minor deviation | 2 | 0,33 | 0,96 |
| | | Prefault | 3 | 0,44 | 0,58 |
| | | Emergency | 4 | 0,44 | 0,23 |
| State of cooling system | $k_{cool.}$ | Normal | 1 | 0,34 | 1,15 |
| | | Minor deviation | 2 | 0,35 | 0,97 |
| | | Prefault | 3 | 0,43 | 0,59 |
| | | Emergency | 4 | 0,42 | 0,23 |
| State of tank | $K_{tank}$ | Normal | 1 | 0,34 | 0,95 |
| | | Minor deviation | 2 | 0,38 | 1,01 |
| | | Prefault | 3 | 0,45 | 0,62 |
| | | Emergency | 2 | 0,54 | 0,56 |

After receiving the results of ANN modeling and analysed data which presented in Tables 1 and 2 obtained the ANN model of the RRI PT in the form:

It is seen from Fig.2 that in the process of formation of the structure of the ANN model of PT, seven inputs and one output of this model were set. Each of the seven inputs has four terms. That is, each set of possible values of input parameters of the model is conventionally divided into four subsets: "normal" values of the input parameter, "miner deviations " of the values of the input parameter, and "prefault" values of the input parameter, "emergency" values of input parameter. The membership degree of each value of input parameter to the corresponding set of values is determined by the Gaussian membership function.

The model is intended for determining the numerical value of the total residual resource coefficient of the transformer, which is why it has one output. This numerical value is found by means of a solution of a linear equation, that describes the dependence of the coefficient of RRI PT on input parameters.

The presented ANN model RRI PT allows us to determine the value of the total residual resource coefficient of the transformer depending on the values of input parameters' RRI by each of the controlled diagnostic parameters. Thus, if each of the RRI of diagnostic parameters will equal 0 relative units (r.u.), then the coefficient of total residual resource (with the error 0.28%) equals 0.003 r.u.; if each of the coefficients of residual resource of diagnostic parameters equals 1. r.u., then the coefficient of total residual resource (with the error 4.1%) equals 0.927 r.u.

$$
\left\{
\begin{array}{l}
\text{IF } k_{wind.} \in \text{"normal" AND } k_{in} \in \text{"normal" AND } k_{BB} \in \text{"normal"} \\
\text{AND } k_{oil} \in \text{"normal" AND } k_{LTC} \in \text{"normal" AND } k_{cool} \in \text{"normal"} \\
\text{AND } k_{tank} \in \text{"normal" THEN} \\
k_{tot.resid.res} = 0{,}6166 \cdot k_{wind} + 0{,}4125 \cdot k_{in} + 0{,}4618 \cdot k_{BB} + 1{,}83 \cdot k_{oil} + 1{,}804 \cdot k_{LTC} + \\
+0{,}0462 \cdot k_{cool.} + 1{,}96 \cdot k_{tank} - 5{,}377 \\
\text{IF } k_{tank} \in \text{"minor deviation" AND } k_{in.} \in \text{"minor deviation"} \\
\text{AND } k_{Bush} \in \text{"minor deviation" AND } k_{oil.} \in \text{"minor deviation"} \\
\text{AND } k_{LTC} \in \text{"minor deviation" AND } k_{cool.} \in \text{"minor deviation"} \\
\text{AND } k_{tank} \in \text{"minor deviation" THEN} \\
k_{tot.resid.res} = -0{,}0393 \cdot k_{wind.} + 0{,}2609 \cdot k_{in.} + 0{,}1086 \cdot k_{Bush.} - 0.37 \cdot k_{oil} - 0{,}1459 \cdot k_{LTC} - \\
-0{,}02387 \cdot k_{cool.} - 0{,}05863 \cdot k_{tank} + 0{,}1288 \\
\text{IF } k_{wind} \in \text{"prefault" AND } k_{in} \in \text{"prefault" AND } k_{Bush.} \in \text{"prefault"} \\
\text{AND } k_{oil} \in \text{"prefault" AND } k_{LTC} \in \text{"prefalt" AND } k_{cool.} \in \text{"prefault"} \\
\text{AND } k_{tank} \in \text{"prefault" THEN} \\
k_{tot.resid.res} = -0{,}2165 \cdot k_{wind.} \cdot - 0{,}3714 \cdot k_{in.} - 0{,}4678 \cdot k_{Bush.} - 0{,}514 \cdot k_{oil} - 0{,}882 \cdot k_{LTC} - \\
-0{,}5302 \cdot k_{cool.} - 1{,}406 \cdot k_{tank} + 3{,}88 \\
\text{IF } k_{wind.} \in \text{"emergency" AND } k_{in} \in \text{"emergency" AND } k_{BB} \in \text{"emergency" AND } k_{oil} \in \text{"emergency"} \\
\text{AND } k_{LTC} \in \text{"emergency" AND } k_{cool.} \in \text{"emergency" AND } k_{tank} \in \text{"emergency" THEN} \\
k_{tot.resid.res} = 0{,}03166 \cdot k_{wind.} - 0{,}06144 \cdot k_{in.} - 0{,}387 \cdot k_{Bush.} + 0{,}06 \cdot k_{oil} + 0{,}3199 \cdot k_{LTC} - \\
-0{,}026 \cdot k_{cool.} - 0{,}006 \cdot k_{tank} + 0{,}003 \\
\ldots
\end{array}
\right.
$$

## Conclusions

According to the plan in Ukraine in the short horizon, the main tasks of the current year will be the restoration and protection of energy facilities, decentralization of the energy system, further strengthening of integration with the European energy space, and increase in import and export opportunities, which not possible to realize without control by power transformers. According to the plan in Ukraine in the short horizon, the main tasks of the current year will be the restoration and protection of energy facilities, decentralization of the energy system, further strengthening of integration with the European energy space, and increase in import and export opportunities, which not possible to realize without control by power transformers. Digitalization of the process determining the technical condition of power transformers in Ukraine condition by the way of creating a Digital Twin of power transformer will speed up this process. The issue of creating a digital twin power transformer requires developing an adequate mathematical model, which can describe all modes and will be available to avoid complicating with incomplete initial data.In this paper creanted ANN model IRR PTm which can be base for developing DT PT.


## *Acknowledgment*

*We want to say thanks to the University of West Bohemia in Pilsen for all round support in this research work. This result was supported by projects 23-PKVV-011 and MSCA4Ukraine ID number 1233365.*



***Authors:*** *Ing., Ph.D., Milan Belik, Department of Electrical Power Engineering, University of West Bohemia, Plzen, Czech Republic, Doc., PhD., Oleksandr Rubanenko, Department of Electrical Stations and Systems, Vinnytsia National Technical University, Khmelnytsky highway 95, 21021 Vinnytsya, Ukraine, Olena Rubanenko, Department of Electrical Stations and Systems, Vinnytsia National Technical University, Khmelnytsky highway 95, 21021 Vinnytsya, Ukraine, olenarubanenko@vntu.edu.ua; Research Innovation Center for Electrical Engineering University of West Bohemia, Pilsen, Czech Republic; Department of Wind Power of Institute Renewable Energy of NAS Ukraine, Kyiv, Ukraine, olenarubanenko@ukr.net.*

REFERENCES


[1] R. Wu, P. Zhu and X. Qin, "CNN-MLP-based transformer digital twin model construction and fault diagnosis and condition evaluation analysis," 2023 IEEE 3rd International Conference on Power, Electronics and Computer Applications (ICPECA), Shenyang, China, 2023, pp. 1081-1088, doi: 10.1109/ICPECA56706.2023.10075826.

[2] "Dozens of these": Ukrenergo showed a transformer that was hit by a Russian missile https://www.unian.ua/economics/energetics/viyna-v-ukrajini-v-ukrenergo-pokazali-transformator-v-yakiy-vluchila-rosiyska-raketa-12048951.html

[3] O. Rubanenko, M. Bajaj, O. Rubanenko and M. Hryshchuk, "Determination of Technical Condition of the Power Transformer by Frequency Response Analysis Method," *2021 IEEE 3rd Ukraine Conference on Electrical and Computer Engineering (UKRCON)*, Lviv, Ukraine, 2021, pp. 395-400, doi: 10.1109/UKRCON53503.2021.9575186.

[4] Fofana, Issouf, and Yazid Hadjadj. 2016. "Electrical-Based Diagnostic Techniques for Assessing Insulation Condition in Aged Transformers" *Energies* 9, no. 9: 679. https://doi.org/10.3390/en9090679

[5] R. Roychowdhury, X. Wu, M. Russ, D. Fleming, and J. Spalding, "Stepping Up to the Future With Power Transformers: Power Transformer Asset Management Strategies: State of the Art and Recommendations for the Future," in IEEE Power and Energy Magazine, vol. 21, no. 2, pp. 40-50, March-April 2023, doi: 10.1109/MPE.2022.3230889.

[6] O. Rubanenko, M. Hryshchuk and O. Rubanenko, "Planning of the experiment for the defining of the technical state of the transformer by using amplitude-frequency characteristic", *Przeland elektrotechniczny*, no. 3, pp. 184-191, 2020.

[7] X. Yang, G. Zhang, S. Yang and Y. Zhou, "Trend Analysis and Fault Diagnosis of Equipment State Based on Transformer Operation Mechanism Modeling," 2022 9th International Forum on Electrical Engineering and Automation (IFEEA), Zhuhai, China, 2022, pp. 868-873, doi: 10.1109/IFEEA57288.2022.10038168

[8] Y. Yang et al., "State Evaluation of Power Transformer Based on Digital Twin," *2019 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI)*, Zhengzhou, China, 2019, pp. 230-235, doi: 10.1109/SOLI48380.2019.8955043.

[9] D. Zou et al., "Research on Digital Twins Technology and Its Future Implementation in Transformer Overload Analysis," *2022 International Conference on Cyber-Physical Social Intelligence (ICCSI)*, Nanjing, China, 2022, pp. 490-495, doi: 10.1109/ICCSI55536.2022.9970559.

[10] J. Zhang, L. Jiang, H. Zhang, S. Zhao, Y. Lin and J. Chen, "Research on On-line State Monitoring Method of Voltage Transformer based on Digital Twins," *2022 4th International Conference on Artificial Intelligence and Advanced Manufacturing (AIAM)*, Hamburg, Germany, 2022, pp. 243-248, doi: 10.1109/AIAM57466.2022.00053.

[11] J. Tuttle. (2022). *Digital Twin: Driving innovation in the energy*

[12] R. J. Hamidi, "Protective Relay for Power Transformers Based on Digital Twin Systems," *2022 IEEE Kansas Power and Energy Conference (KPEC)*, Manhattan, KS, USA, 2022, pp. 1-6, doi: 10.1109/KPEC54747.2022.9814786.ving-innovation-in-the-energy-sector/

[13] O. Rubanenko, O. Kazmiruk, V. Bandura, V. Matvijchuk, and O. Rubanenko, "Determination of optimal transformation ratios of power system transformers in conditions of incomplete information regarding the values of diagnostic parameters," *Eastern-European Journal of Enterprise Technologies*, Article vol. 4, no. 3-88, pp. 66-79, 2017.