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COMPLEX MODELING OF TECHNICAL CONDITION AND REGIMES OF VOLTAGE REGULATION OF CONTROL DEVICES UNDER LOAD OF POWER TRANSFORMERS

The scientific work considers issues (tasks) of the technical condition assessment and voltage regulation in power system load nodes using power transformers on-load tap-changer devices by fuzzy modeling methods. A linguistic model of TC class determining and decision-making on the operation strategy for OLTC devices is presented. A fuzzy algorithm for voltage regulation in load nodes by OLTC devices is proposed, taking into account resource constraints. A voltage control modes test study under changing the nodal load was conducted for the consumers power supply system of the distribution network.

Keywords: power transformers; technical condition; linguistic model; voltage regulation; fuzzy logic.

Fig.: 5. Tables: 3. References: 17.

Relevance of the research. Amidst the liberalization of the electricity industry of Ukraine, the requirements for ensuring the reliability of electricity supply to consumers, in particular, the quality of electricity, are significantly increasing. Deviation of electricity quality parameters, of which main one is the voltage at the consumer terminals, is strictly regulated and allowed in normal operation $\pm 5\%$ of rated voltage and $\pm 10\%$ in emergency [1; 2]. However, the analysis of accidents in modern power systems (PSs) with power plants of different types shows that the probability of accidents in PSs with significant deviations of voltage and frequency is not completely excluded. The basic factor, which essentially affects the reliability of the electric power industry is the solid deterioration of electrical equipment, including power transformers (PTs) which are the most common and the most responsible elements of the PS [2; 3]. The connection of distributed generation sources (DGSs) also exacerbates the problem of keeping the voltage within acceptable limits in terms of load changes and the topology of the electrical network, as voltage reduction can lead to a decrease power generation by DRG [4]. Therefore, the issue of automatic voltage stabilization in the PS load nodes and on the buses of the power plant's own needs in all operation modes is an urgent task.

Problem statement. Among the various methods of voltage regulation [1; 5; 6; 7; 8; 9] currently available in the PS, the most common is the regulation under load at the PT terminals by changing the transformation coefficient [1; 5] using on-load tap-changer (OLTC). The OLTC PT operation practice shows that the resource of its elements is small and therefore the repair service involves the PT decommission with a corresponding interruption of electricity supply to consumers. The accident rate analysis of high-power PTs for 1985-2010 shows that the share of emergencies caused by OLTC failures reaches 15-40% [10]. As a result, automatic voltage regulators are often disconnected from the mains, which reduces the electricity quality.

Thus, an important task is the development of new and advanced basic methods and models for evaluating the technical condition (TC) and the algorithms for regulating the voltage in load nodes driven by the OLTC PT.

Existing traditional methods and models of TC PT diagnosing are based on the use of "strict norms" for the parameters values that separate one TC class from another, which are enshrined in the relevant regulations [2; 11]. Incomplete and discrete information about TC of OLTC,

which is due to the periodicity of parameter measurements, as well as significant subjectivity in the expert TC determination by qualified personnel of the operating organizations repair service severely complicates the task of assessing TC of OLTC PT [11; 12].

The difficulty in identifying analytical relationships between TC parameters changes and TC class of an object requires the use of data mining methods to build appropriate models for estimating TC of OLTC [2; 13; 14], which allows presenting in a single form heterogeneous information about the object.

In this case, using fuzzy set theory is effective both for the TC diagnostic tasks of OLTC devices and for the selection and formation of voltage control algorithms. Thus, it is necessary to develop a linguistic model for assessing the TC of OLTC based on data mining and to build and implement algorithms for intelligent control of voltage control modes in distribution networks by OLTC taking into account resource constraints.

Analysis of recent research and publications. Currently, there are a bulk works devoted to the development of models for assessing TC PT and its individual elements based on a set of measurements and tests [2; 3; 6; 7; 11; 15; 16] and algorithms for voltage regulation in the PS distribution networks. [2; 9; 11] dealt with the TC index definition problem, identification and defect development level in terms of deterministic and probabilistic and fuzzy nature of information, but TC assessment issues of OLTC devices were not considered. The papers [2; 3; 12] presented models for estimating and forecasting TC individual elements, particularly, OLTC PT devices, but they did not identify resource constraints and did not consider voltage control modes. In [1; 15; 16] traditional and fuzzy models and algorithms for voltage regulation at the supply nodes by OLTC PT devices were proposed, but their resource limits were not considered.

Uninvestigated parts of a common problem. Despite a bulk of works on TC modeling as a whole PT and its individual elements (including OLTC), as well as voltage control modes in distribution networks, there is a complex TC modeling problem, identification and consideration resource constraints of OLTC devices voltage regulation in fuzzy voltage regulation models in load nodes by PT voltage regulators.

Research objective. The purpose of the article is to build a complex fuzzy mathematical model for estimating the technical condition and OLTC voltage regulation algorithms of oil PT. To achieve the above, it is necessary to solve the following tasks:

- to identify measurements groups, tests and criteria for OLTC TC diagnosing;
- to form input linguistic variables and membership functions of their term sets and TC classes of OLTC devices fuzzy model;
- to develop a fuzzy knowledge base of the linguistic model for determining the TC class and decision-making strategy of OLTC devices operation;
- to develop a fuzzy algorithm and software for voltage regulation in the load node by OLTC PT devices taking into account their TC;
- to conduct a test study of voltage control modes taking into account the OLTC resource constraints.

The statement of basic material. *Estimation linguistic model of OLTC device.* The most common OLTC device defects and damage are: oil characteristics deterioration, the contactor contacts overheating, wearing of contactor seals and selector contacts, OLTC device mechanical wear, drive kinematics damage [1; 8; 9; 10; 12]. The following tests and measurements are used to evaluate TC of OLTC device [2; 10]: dissolved gases chromatographic analysis in the OLTC contactor (DGCA), physico-chemical analysis of the contactor oil characteristics, determination TC parameters of OLTC device, measuring the parameters of the conductive parts of the contactor.

Within the possible change range in the TC parameters of OLTC, the following areas of normal and abnormal operation modes can be defined: d1- «normal operation area», range from parameter values after commissioning (or after repair) to values that limit the normal operation area; d2 - «risk

operation area», the parameters values range that limit the normal operation area to the maximum allowable values in operation; d3- «operation area in the defect presence (pre-emergency state)», at least one of OLTC parameters exceeds the maximum permissible values in operation.

Consider the criteria for diagnosing OLTC TC based on some types of results of tests and measurements.

Linguistic variables and diagnostic TC parameters term sets of the fuzzy knowledge base of the mathematical model for assessing the TC OLTC, which are determined by the DGCA results (gas concentration H₂, C₂H₂, C₂H₆, CH₄, C₂H₄, CO, CO₂), physico-chemical analysis (tangent delta of dielectric losses in transformer oil *tgδ*, breakdown voltage *U_{np}*, moisture content in the transformer oil of contactor *W*, acid number KOH), drive mechanism monitoring (drive electric motor current *I*), current-carrying parts tests of the transformer and contactor (the transient contacts resistance of the contactor *R*) are as follows [2,10]:

$C_1 = \{T_{C1}^L, T_{C1}^M, T_{C1}^B\}$ - gases ratio $M_1 = \frac{C_2H_4}{C_2H_2}$, r.u.; $C_2 = \{T_{C2}^L, T_{C2}^M, T_{C2}^B\}$ - gases ratio $M_2 = \frac{CH_4 + C_2H_6 + C_2H_4}{C_2H_2}$, r.u.; $C_3 = \{T_{C3}^L, T_{C3}^M, T_{C3}^B\}$ - electric motor current of the OLTC drive *I*, A ; $C_4 = \{T_{C4}^L, T_{C4}^M, T_{C4}^B\}$ - transient contacts resistance of contactor, *R*, Ohm; $C_5 = \{T_{C5}^L, T_{C5}^M, T_{C5}^B\}$, $C_6 = \{T_{C6}^L, T_{C6}^M, T_{C6}^B\}$, $C_7 = \{T_{C7}^L, T_{C7}^M, T_{C7}^B\}$, $C_8 = \{T_{C8}^L, T_{C8}^M, T_{C8}^B\}$, $C_9 = \{T_{C9}^L, T_{C9}^M, T_{C9}^B\}$, $C_{10} = \{T_{C10}^L, T_{C10}^M, T_{C10}^B\}$, $C_{11} = \{T_{C11}^L, T_{C11}^M, T_{C11}^B\}$ – hydrogen concentrations dissolved in oil (H₂), μl / l; methane (CH₄), μl / l; ethane (C₂H₆), μl / l, ethylene (C₂H₄), μl / l; acetylene (C₂H₂), μl / l; carbon monoxide (CO), μl / l; carbon dioxide (CO₂), μl / l in accordance; $C_{12} = \{T_{C12}^L, T_{C12}^M, T_{C12}^B\}$ – (*tgδ*) %; $C_{13} = \{T_{C13}^L, T_{C13}^M, T_{C13}^B\}$ – *U_{np}*, kV; $C_{14} = \{T_{C14}^L, T_{C14}^M, T_{C14}^B\}$ – *W*, g/t; $C_{15} = \{T_{C15}^L, T_{C15}^M, T_{C15}^B\}$ – KOH, mgKOH/g oil.

DGCA results interpretation. In a normal OLTC operation, the gas composition in contactors corresponds to the arc oil destruction (due to arc discharge) with the main gases H₂ and C₂H₂. In the contacts wear process, their heating and overheating levels increase in accordance with the criteria (table 1) and the C₂H₄ concentration increase relatively to C₂H₂. To diagnose contact damage, the gases ratio, which characterize heating C₂H₂, C₂H₆ and CH₄ to the "arc" gas C₂H₂, is used $M_1 = \frac{C_2H_4}{C_2H_2}$, $M_2 = \frac{CH_4 + C_2H_6 + C_2H_4}{C_2H_2}$.

Table 1

Contacts overheating criteria in the contactor

Gases ratio	«Normal mode»	«Needs attention»	Possible damage
M ₁	<1	≥1; ≤5	≥5
M ₂	<0,8	≥0,8; ≤4	≥4

Source: designed by the authors.

The main factors and parameters that significantly affect the OLTC failure risk during operation are: contactor contacts wear, characterized by the gases ratio (M₁) and (M₂); electric motor current of the OLTC drive *I*; transient contacts resistance of contactor, *R*. The generated input linguistic variables of the fuzzy model for estimating the TC OLTC are: $C_1 = \{T_{C1}^L, T_{C1}^M, T_{C1}^B\}$ – gases ratio $M_1 = \frac{C_2H_4}{C_2H_2}$, r.u.; $C_2 = \{T_{C2}^L, T_{C2}^M, T_{C2}^B\}$ – gases ratio $M_2 = \frac{CH_4 + C_2H_6 + C_2H_4}{C_2H_2}$, r.u.;

$C_3 = \{T_{C3}^L, T_{C3}^M, T_{C3}^B\}$ – electric motor current of the OLTC drive I , A; $C_4 = \{T_{C4}^L, T_{C4}^M, T_{C4}^B\}$ – transient contacts resistance of contactor, R , Ohm.

The following values are assigned to the term sets $T_{C_i}^j$ of input linguistic variables: $T_{C_i}^L$ – low parameter value (correspond to OLTC state – «d1»); $T_{C_i}^M$ – medium parameter value (correspond to OLTC state – «d2»); $T_{C_i}^B$ – big parameter value (correspond to OLTC state – «d3»). Existing normative documents the actual TC practice using traditional methods shows that the criterion parameters values fluctuate within (5 ÷ 10) % [1; 2]. Therefore, the fixed norms vagueness in the linguistic model can be limited to ± (5-7) %. The terms membership functions of the model input linguistic variables for TC OLTC estimating are presented in Fig. 1.

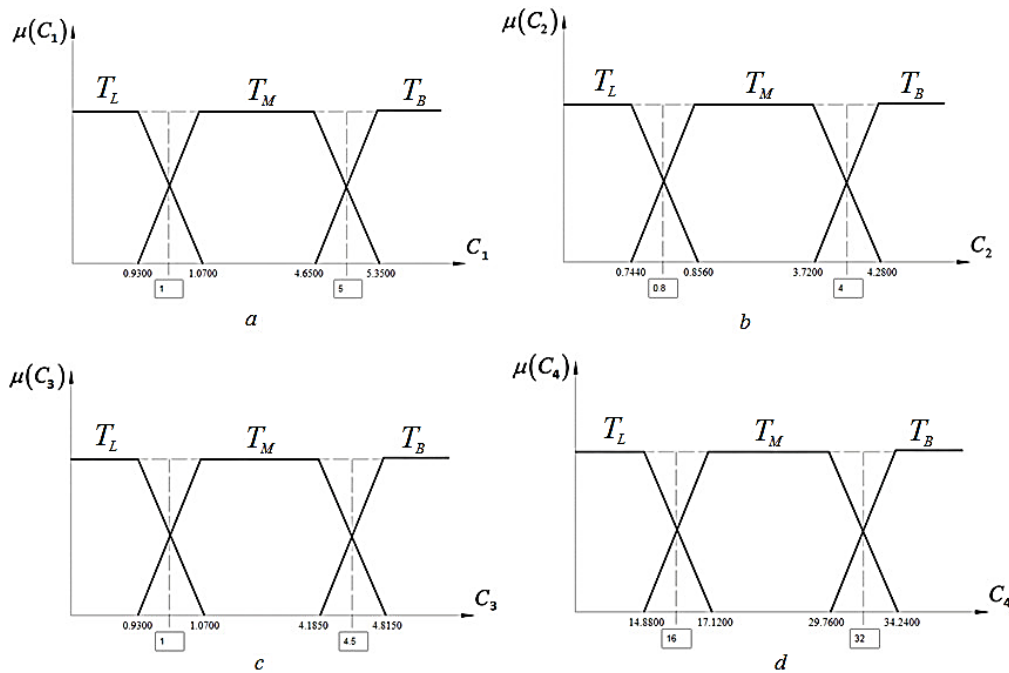


Fig. 1. Basic membership functions forms of fuzzy terms of input linguistic variables: a – variant 1, b – variant 2, c – variant 3, d – variant 4

Source: designed by the authors.

The developed rules base for the TC OLTC classification has the form:

1. IF ($C_1 = T_{C1}^L$), AND ($C_2 = T_{C2}^L$), AND ($C_3 = T_{C3}^L$), AND ($C_4 = T_{C4}^L$), THEN $d = d_1$
2. IF ($C_1 = T_{C1}^L$), AND ($C_2 = T_{C2}^L$), AND ($C_3 = T_{C3}^L$), AND ($C_4 = T_{C4}^M$), THEN $d = d_1$
3. IF ($C_1 = T_{C1}^L$), AND ($C_2 = T_{C2}^L$), AND ($C_3 = T_{C3}^M$), AND ($C_4 = T_{C4}^L$), THEN $d = d_1$
-
25. IF ($C_1 = T_{C1}^M$), AND ($C_2 = T_{C2}^L$), AND ($C_3 = T_{C3}^M$), AND ($C_4 = T_{C4}^M$), THEN $d = d_2$
26. IF ($C_1 = T_{C1}^M$), AND ($C_2 = T_{C2}^L$), AND ($C_3 = T_{C3}^M$), AND ($C_4 = T_{C4}^B$), THEN $d = d_2$
27. IF ($C_1 = T_{C1}^M$), AND ($C_2 = T_{C2}^L$), AND ($C_3 = T_{C3}^B$), AND ($C_4 = T_{C4}^L$), THEN $d = d_2$
-
79. IF ($C_1 = T_{C1}^B$), AND ($C_2 = T_{C2}^B$), AND ($C_3 = T_{C3}^B$), AND ($C_4 = T_{C4}^L$), THEN $d = d_3$
80. IF ($C_1 = T_{C1}^B$), AND ($C_2 = T_{C2}^B$), AND ($C_3 = T_{C3}^B$), AND ($C_4 = T_{C4}^M$), THEN $d = d_3$
81. IF ($C_1 = T_{C1}^B$), AND ($C_2 = T_{C2}^B$), AND ($C_3 = T_{C3}^B$), AND ($C_4 = T_{C4}^B$), THEN $d = d_3$

TC OLTC classification. According to [13,14], the classification problem is to assign the object given by the informative features vector $X = (x_1, x_2, \dots, x_n)$, to one of the previously described classes $\{d_1, d_2, \dots, d_m\}$.

For the above rules set, the object belonging degree $X^* = (x_1^*, x_2^*, \dots, x_n^*)$ to the classes d_j is defined:

$$\mu_{dj} = (X^*) = \max_{p=1..k_j} w_{jp} \min_{i=1..n} (\mu_{jp}(x_i^*)), j = 1, m,$$

where $\mu_{jp}(x_i)$ – login membership function x_i fuzzy term $a_{i,jp}$; $a_{i,j1}$ – fuzzy term by which the variable x_i is estimated in the rule with the number jp , $p = 1..k_j$; k_j – the number of rules describing the class d_j .

The class with the maximum affiliation degree is chosen as a solution:

$$y^* = \arg \max (\mu_{d1}(X^*), \mu_{d2}(X^*), \dots, \mu_{dm}(X^*)).$$

The functional connections structure of the linguistic TC OLTC assessment model is shown in Fig. 2.

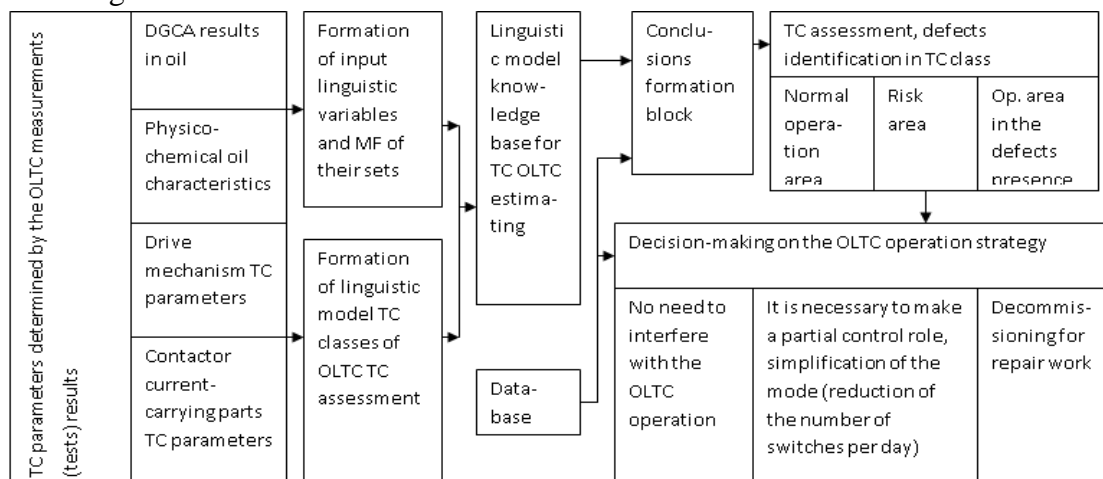


Fig. 2. The functional connections structure of the linguistic TC OLTC assessment model
Source: designed by the authors.

For 110 kV PT, in particular, transformer type TDN-40000/110 substation power supply system (Fig. 4), the initial data and model-experimental TC OLTC diagnostics results are shown in tables 2 and 3 for different combinations of vehicle parameters in 15 operating modes.

Table 2

The TC OLTC parameters monitoring results in different operating modes

№	C ₂ H ₆ µg / l	C ₂ H ₄ µg / l	C ₂ H ₂ µg / l	CH ₄ µg / l	$\frac{C_2H_4}{C_2H_2}$	$\frac{CH_4 + C_2H_6 + C_2H_4}{C_2H_2}$	I, A	R, µOhm
1/2	85/275	194/325	37/120	4,5/3,7	5,243/2,7	7,662/4,15	2,3/4,8	16,16/31
3/4	50/190	50/302	10/60,4	1/5	5/5	10,1/8,22	1/3,8	16/16,9
5/6	51/25	95/10	46/10	4,5/0,5	2/1	3,27/3,55	2/1	17/16,3
7/8	2/110	25/176	30/60,4	0,2/10	0,83/2,91	0,9/4,9	0,85/2,5	15,35/13,5
9/10	60/88	185/125,5	47,8/87	21,5/15,6	3,8/3,2	5,57/4,1	0,41/1,05	16,89/15,86
11/12	63,5/16	98/24	133/26	26/1,5	0,73/0,923	1,4/1,596	0,5/2	15/17,5
13/14	90/54	156/86	45/48	30/54	4,466/1,8	6,133/4,1	0,8/4,65	16/25,5
15	34	47	120	14	0,38	0,8	0,49	14,9

Source: designed by the authors.

Table 3

The TC OLTC classification results of the power transformer

№	The belonging function value to the TC OLTC class			The MF maximum value	Defined TC class
	μ_{D1}	μ_{D2}	μ_{D3}	μ_{Dmax}	
15	0,59	0,054	0	0,59	d1
7	0,79	0,21	0	0,79	d1
13	0	0,5	0	0,5	d2
9	0	0,9	0	0,9	d2
8	0	1	0	1	d2
1	0	0,153	0,572	0,572	d3
14	0	0,313	0,69	0,69	d3

Source: designed by the authors.

Fuzzy mathematical model of voltage regulation in load nodes by OLTC. The analysis of existing methods of voltage regulation in electrical networks by OLTC has shown that the voltage regulation laws have implemented in automatic voltage regulators, providing the required regulation quality, do not take into account the available OLTC resource [1; 5; 6; 15; 16], which reduces their operation reliability. Based on the diagnostics results in the complex mathematical model, the TC OLTC is determined and restrictions on the allowable switches number for a certain specified service life are formed. This parameter is an additional input variable in the fuzzy Mamdani algorithm [13; 17] voltage regulation in the load node by OLTC devices.

The following basic principles are implemented in the algorithm: the voltage on the consumers busbars must be maintained within the normalized DSTU; the operation OLTC PT must be blocked in the event of a short-term voltage failure due to short circuits, starts and self-starting of electric motors. The following parameters are fed to the input of the controller, which operates according to the Mamdani algorithm: voltage on the consumer’s busbars; voltage change rate and limitation on the number of switches during the observation period; the OLTC current position, and the output is removed from the switching direction and the time for which this switching must be performed. The terms of the input and output linguistic variables of the fuzzy voltage regulator are given below: voltage in the load node $U = \{T_{DH}^U, T_H^U, T_{MH}^U, T_B^U, T_{DB}^U\}$; voltage change rate $dU / dt = \{T_H^{dU/dt}, T_{BH}^{dU/dt}, T_{\Pi}^{dU/dt}\}$; OLTC movement direction $NAP = \{T_{BH}^{PIH}, T_H^{PIH}, T_{BB}^{PIH}\}$; OLTC device branches position $X = \{T_{HC}^X, T_C^X, T_{BC}^X\}$; switch delay $t_3 = \{T_{DM}^3, T_M^3, T_C^3, T_B^3, T_{DB}^3\}$; number of switches $N_{перем} = \{T_M^{N_{перем}}, T_C^{N_{перем}}, T_B^{N_{перем}}\}$

Membership functions graphs of the input and output linguistic variables terms are shown in Fig. 3.

The rule base fragment in the voltage regulation system of fuzzy Mamdani algorithm in the load node, which is built taking into account the above principles and approaches, has the following form:

1. IF $(U = T_H^U)$ AND $(X = T_{HC}^X)$ AND $(dU / dt = T_H^{dU/dt})$ AND $(N_{перем} = T_M^{N_{перем}})$ THEN $t_3 = T_{DM}^3$ AND $NAP = T_{BH}^{PIH}$.
2. IF $(U = T_H^U)$ AND $(X = T_{HC}^X)$ AND $(dU / dt = T_H^{dU/dt})$ AND $(N_{перем} = T_C^{N_{перем}})$ THEN $t_3 = T_{DM}^3$ AND $NAP = T_{BH}^{PIH}$.
3. IF $(U = T_H^U)$ AND $(X = T_{HC}^X)$ AND $(dU / dt = T_H^{dU/dt})$ AND $(N_{перем} = T_B^{N_{перем}})$ THEN $t_3 = T_{DM}^3$ AND $NAP = T_{BH}^{PIH}$.

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33. IF $(U = T_{MH}^U)$ AND $(dU / dt = T_{BH}^{dU/dt})$ AND $(N_{перем} = T_B^{N_{перем}})$ THEN $t_3 = T_{ДБ}^3$ AND $NAP = T_H^{PPIH}$.

34. IF $(U = T_{MH}^U)$ AND $(dU / dt = T_{II}^{dU/dt})$ AND $(N_{перем} = T_C^{N_{перем}})$ THEN $t_3 = T_B^3$ AND $NAP = T_H^{PPIH}$.

35. IF $(U = T_{MH}^U)$ AND $(dU / dt = T_H^{dU/dt})$ AND $(N_{перем} = T_B^{N_{перем}})$ THEN $t_3 = T_{ДБ}^3$ AND $NAP = T_H^{PPIH}$.

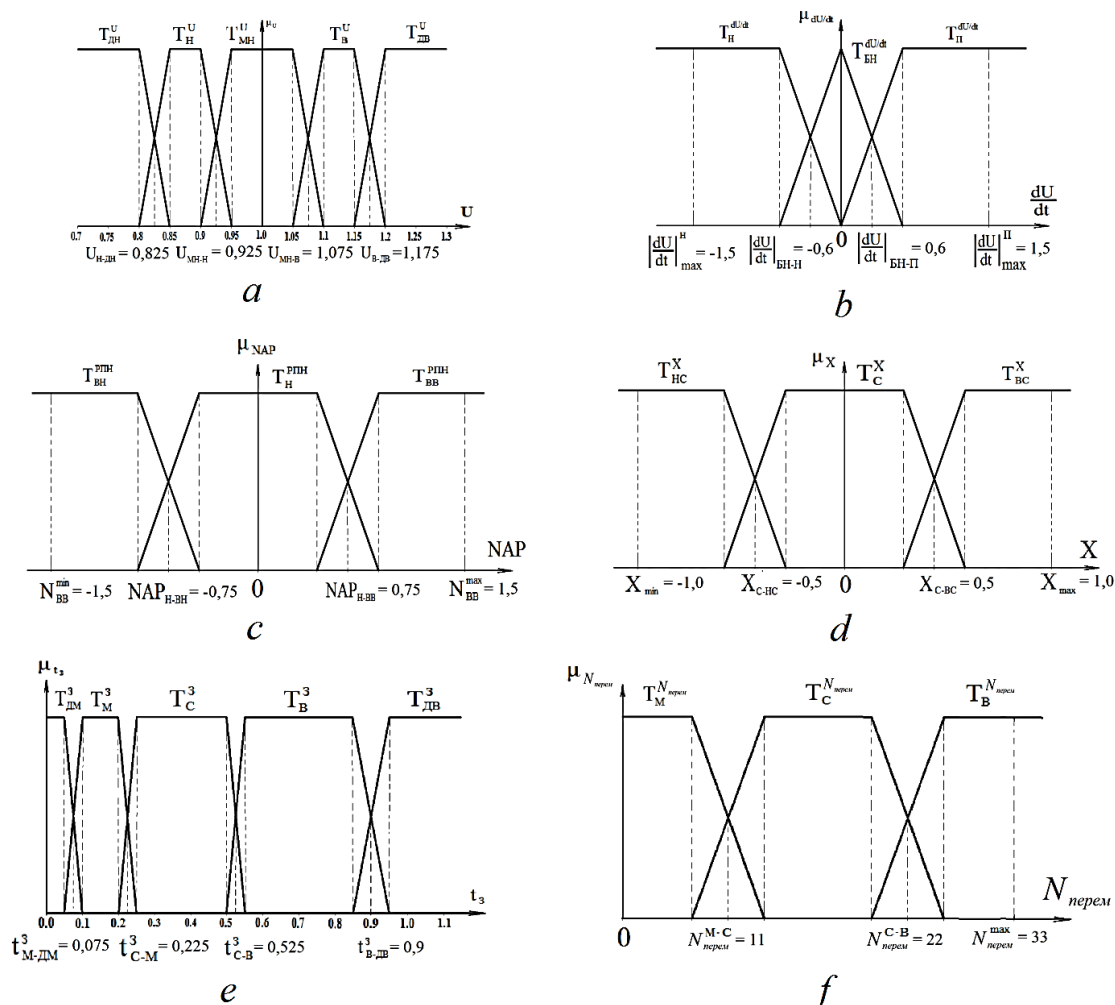


Fig. 3. Membership functions graphs of the input and output linguistic variables terms of fuzzy controller:

a – voltage in the load node, b – voltage change rate, c – OLTC movement direction, d – OLTC device branches position, e – switch delay, f – number of switches

Source: designed by the authors.

To test the developed complex mathematical model, the TC OLTC and the voltage control modes study in the load node for the power supply circuit, which is shown on fig. 4, were performed, which the elements parameters have the following values: transformer type TDN-40000/110 – capacity $S=40$ MVA, transformation coefficient-115/11, short circuit voltage $U_k = 10,5$ % ; overhead line ПЛ – total active and inductive resistance $r_{пл} = 13,6$ Ohm,

$x_{nl} = 18,4 \text{ Ohm}$, length $l_{nl} = 40 \text{ km}$; cable line КЛІ – length $l_{клі} = 12 \text{ km}$, total active and inductive resistance $r_{клі} = 1,014 \text{ Ohm}$, $x_{клі} = 0,456 \text{ Ohm}$; load – full capacity $S_H = 30 \text{ MVA}$, rated load voltage $U_H = 10,5 \text{ kV}$, capacity factor $\cos \varphi = 0,6$.

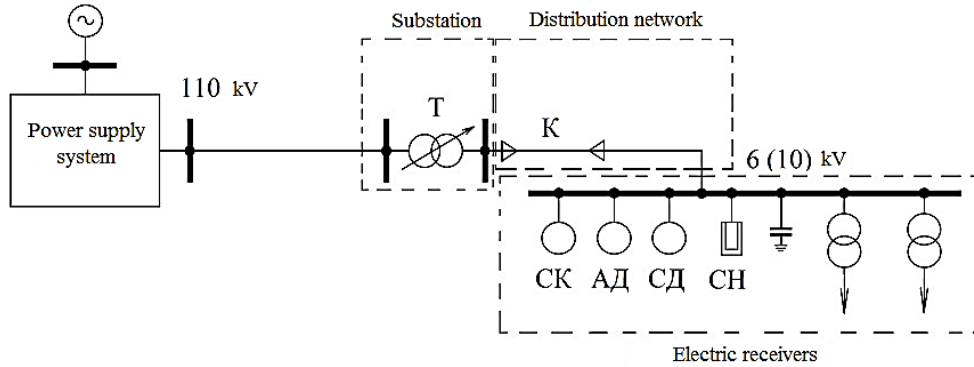


Fig. 4. The load node consumers power supply system scheme

Source: designed by the authors.

The voltage level on the busbars in the load change conditions is maintained within acceptable limits by the PT fuzzy voltage regulator, which implements the counter-regulation law and is determined from the equation:

$U_H = U_C - I_{ЛЗ} \cdot Z_{3\phi}$, where U_H – voltage on the consumer busbars; U_C – voltage on the infinite power system busbars (voltage on the secondary winding of the transformer); $Z_{3\phi}$ – the connection resistance between the consumer busbar and the infinite power system; $I_{ЛЗ}$ – current in the communication line of the power supply circuit.

The study results of voltage regulation processes in the distribution network for various limitations of the switches number are shown in fig. 5, which are determined by the results of the TC OLTC evaluation.

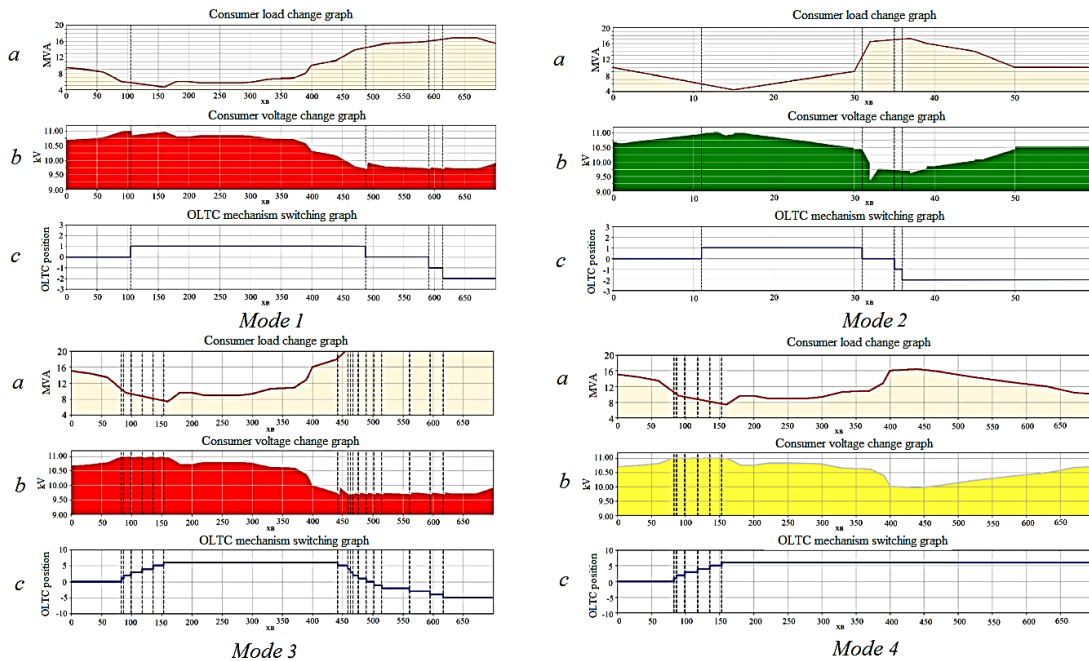


Fig. 5. The load changing processes (a), the voltage in the load node (b) and the OLTC branches position (c) in different operating modes

Source: designed by the authors.

Conclusions. Ensuring the required level of operational reliability, electricity quality of modern PSs requires considering TC and the PT service life in the implementation of voltage control algorithms in the load nodes. A fuzzy model of TC class determination and decision-making on the OLTC operation strategy has been developed. A fuzzy algorithm is proposed and software for voltage regulation in the load node by OLTC PT is developed taking into account their TC. Modeling and test calculations of voltage control modes in the load nodes of the PS distribution network are performed, given the OLTC resource limitations. Studies have shown the feasibility and effectiveness of TC fuzzy modeling and voltage control modes by OLTC device, in particular, the required voltage regulation quality in the load nodes is provided with fewer switches.

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КОМПЛЕКСНЕ МОДЕЛЮВАННЯ ТЕХНІЧНОГО СТАНУ І РЕЖИМІВ РЕГУЛЮВАННЯ НАПРУГИ ПРИСТРОЇВ РЕГУЛЮВАННЯ ПІД НАВАНТАЖЕННЯМ СИЛОВИХ ТРАНСФОРМАТОРІВ

Нині з розвитком ринкових відносин в електроенергетиці України, старінням основних фондів, збільшенням частки відновлюваних джерел енергії загострюється проблема забезпечення режимної надійності сучасних ЕЕС унаслідок підвищення вірогідності виникнення аварійних ситуацій, які супроводжуються значним відхиленням напруги у вузлах навантаження. Найбільш поширеним способом регулювання напруги є регулювання пристроями регулювання напруги під навантаженням (РПН) СТ, які є достатньо ненадійними елементами СТ з малим ресурсом працездатності, що спричиняє часті відключення автоматичних регуляторів напруги СТ від мережі зі зниженням якості напруги. Складність виявлення аналітичних залежностей між зміненням параметрів ТС і класом ТС об'єкта потребує використання методів інтелектуального аналізу даних для розробки моделей оцінки ТС пристроїв РПН СТ та побудови алгоритмів управління режимами регулювання напруги в розподільних мережах з урахуванням ресурсних обмежень об'єкта.

Аналіз досліджень і останніх публікацій, присвячених питанням розробки математичних моделей оцінки ТС і ризику відмови СТ та пристроїв РПН СТ, способам і алгоритмам регулювання напруги у вузлах навантаження ЕЕС показав, що існує необхідність удосконалення математичного і програмного забезпечення оцінки ТС, ризику відмови СТ та створення ефективних алгоритмів регулювання напруги у вузлах навантаження з відповідальними споживачами.

Незважаючи на значну кількість робіт, присвячених моделюванню технічного стану окремих елементів СТ, зокрема, пристроїв РПН та режимів регулювання напруги у розподільних мережах, існує задача комплексного моделювання ТС, визначення і врахування ресурсних обмежень пристроїв РПН в нечітких моделях регулювання напруги у вузлах навантаження регуляторами напруги СТ.

Метою роботи є побудова комплексної математичної моделі оцінки технічного стану і алгоритмів регулювання напруги пристроїв РПН силових масляних трансформаторів.

Запропоновано при реалізації алгоритмів регулювання напруги у вузлах навантаження ЕЕС пристроями РПН СТ комплексний підхід, що ґрунтується на врахуванні ТС і ресурсу працездатності об'єкта. Розроблено лінгвістичну модель визначення класу ТС і прийняття рішень щодо стратегії експлуатації пристроїв РПН СТ; побудовано нечіткий алгоритм і розроблено програмне забезпечення регулювання напруги у вузлі навантаження пристроями РПН СТ з урахування їх ТС; проведено тестове дослідження режимів регулювання напруги у вузлі навантаження з урахуванням ресурсних обмежень для пристроїв РПН СТ.

Ключові слова: силові трансформатори; технічний стан; лінгвістична модель; регулювання напруги; нечітка логіка.

Рис.: 5. Табл.: 3. Бібл.: 17.