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Regulating steady-state voltage deviation using fuzzy logic

***Abstract**. A model of regulation of steady voltage deviation using fuzzy logic was proposed for the problem of normalizing voltage quality in the network. On the basis of simulation, the effectiveness of the proposed algorithms is shown. The control algorithm based on fuzzy logic is considered as an alternative to the transition from analogue control to the digital tap-changer control system. The results of the work can be used in the design of the substation for introduction into the power system.*

***Streszczenie.** W artykule zaproponowano model regulacji stałego odchylenia napięcia z wykorzystaniem logiki rozmytej dla problemu normalizacji jakości napięcia w sieci. Na podstawie symulacji wykazano skuteczność proponowanych algorytmów. Algorytm sterowania oparty na logice rozmytej jest rozważany jako alternatywa dla przejścia od sterowania analogowego do cyfrowego systemu sterowania przełącznikiem zaczepów. Wyniki pracy mogą być wykorzystane przy projektowaniu podstacji do wprowadzenia do systemu elektroenergetycznego.(**Regulacja odchylenia napięcia w stanie ustalonym za pomocą logiki rozmytej**)*

Keywords: distribution network, fuzzy logic control algorithm, electrical engineering, automatics
Słowa kluczowe: sieć dystrybucyjna, algorytm sterowania logiką rozmytą, elektrotechnika, automatyka

Introduction

One of the important requirements for power supply is ensuring the quality of electricity, which is understood as the degree of compliance of quality indicators with accepted standards. Deviation of voltage and other quality indicators from established standards significantly affects the operation of electrified equipment and electrical networks, leading to an electromagnetic and technological component of economic damage. Therefore, one of the important energy problems in Ukraine and around the world is the normalization of electricity quality indicators.

Subject to compliance with established power quality standards, electromagnetic compatibility of electrical networks of energy supply organizations and electrical networks of electrical energy consumers is ensured. Voltage deviations from nominal values occur due to daily, seasonal and technological changes in the electrical load of consumers, changes in the power of compensating devices, voltage regulation by generators of power plants and at power system substations, changes in the layout and parameters of electrical networks. The quality of delivered electricity, like quality of other goods and services, is difficult to define and quantify. There is not one accepted definition of quality electricity. The quality is mainly determined by the quality of the voltage waveform, as it is impossible to control the currents drawn by customer loads. Voltage quality is not only the responsibility of the network operator but also, in certain respects, depends on producers and customers [1]. EN 50160:2014 is nominated voltage deviation at the terminals of electrical energy receivers [2]. Normally permissible and maximum permissible values of voltage deviation, which are equal to ± 5% and ± 10% of the nominal value of the voltage, respectively, and at the points of common connection of consumers of electric energy must be established in energy supply contracts for the hours of minimum and maximum loads in the power system, taking into account the need compliance with the norms of the standard on the conclusions of the receivers of electrical energy in accordance with regulatory documents.

Literature review

The article describes a device for regulating alternating voltage, in which semiconductor power switches are used to switch the tap-offs of a non-contact tap-changer device [3-5]. Also known is a device for switching branches of the regulating winding of a transformer under load, which contains two vacuum switches in unloading with thyristor switching and contactors [6-9]. A similar device for regulating the voltage of a power transformer with switching of the disordering of the secondary winding of the transformer is described [10-13]. The article describes the definition of acceptable ranges of regulation of slow voltage changes by means of simulation modeling. The on-load tap-changer device is an element with a limited switching resource [14,15]. Mechanical on-load tap-changer devices have a disordering switching time of ≥ 5. Contactless tap-changer devices, which use semiconductor power switches, do not have these disadvantages [16-20]. Transformers equipped with such devices have a disordering switching time of ≥10 ms, and the switching itself is not accompanied by the appearance of higher harmonics, accordingly, the dynamic stability of the voltage regulation system is improved [21, 22]. The additional voltage device (AVD) is a constructively and functionally finished device and serves to strengthen the power supply of the contact network. The additional voltage device stabilizes the contact network voltage by adjusting the output voltage level of the traction substation depending on the current load [23-26]. The existing on-load tap-changer control systems have the following disadvantages: high cost and a limited number of switches, which reduces the quality of regulation. The device presented in the article does not protect keys from short-circuit currents, and higher harmonics appear in the network in intermediate operating modes [27-31]. The disadvantage of the method of voltage regulation given in the article is that the switching is carried out on the secondary side of the power transformer, where with significant power the current of the transformer reaches several thousand amperes [32-34]. Thus, each key will consist of several parallel thyristors, which is economically unprofitable. For accurate switching of positions and efficient operation of the on-load tap-changer device, it is necessary to change the algorithmic component of on-load tap-changer control systems [35-38].

Materials and methods

One of the main requirements for electricity supply is ensuring the quality of electrical energy, which is understood as the degree of compliance of quality indicators with the accepted norms [10]. Deviation of voltage and other quality indicators from established standards significantly affects the operation of electrified equipment and electrical networks, leads to electromagnetic and technological components of economic loss. In compliance with the established standards of electricity quality, electromagnetic compatibility of the electrical networks of energy supply organizations and the electrical networks of electricity consumers is ensured. Deviation of voltage from nominal values occurs due to daily, seasonal and technological changes in the electric load of consumers, changes in the power of compensating devices, voltage regulation by generators of power plants and at substations of the power system, changes in the circuit and parameters of electric networks. The control algorithm based on fuzzy logic is considered as an alternative to the transition from analogue control to the on-load tap-changer digital control system. Therefore, a control algorithm based on fuzzy logic can be used to regulate the steady-state voltage deviation. To simulate this system, it is best to use the Fuzzy Logic Toolbox application, which is included in the MATLAB program package. The steady deviation of the voltage "Uu" is presented in a fuzzy form, that is, the input parameters of the fuzzy output system are considered four fuzzy variables corresponding to the phase voltages and the switching position of the on-load tap-changer device: "Phase A", "Phase B", "Phase C" and "Switching of the on-load tap-changer device ". And the output parameters are four fuzzy variables: "Position of the on-load tap-changer device", "Disconnection of part of the load", "Inclusion of additional load" and "Inclusion of the additional voltage device". The function of belonging to the steady-state voltage indicators (as an example below - Fig. 1), where U_n is the nominal value of the corresponding voltage deviation; $\mu\delta U_{yL}$, $\mu\delta U_{yN}$, $\mu\delta U_{yH}$ are, respectively, a function of belonging to indicators of established normal, low, and high voltage [11, 12]. The set Tu={"UAlow", "UAmid", "UAhigh"} (as an example below - Fig. 2). The membership functions of the terms of sets Tu are chosen in accordance with the norms of the standard and look as follows:

(1) $$\mu\delta U_{yL} = \max\{0, \min\{1, \frac{0{,}95U_n - U}{0{,}05U_n}\}\},$$

(2) $$\mu\delta U_{yN} = \max\{0, \min\{1, \frac{U - 0{,}9U_n}{0{,}05U_n}, \frac{1{,}1U_n - U}{0{,}05U_n}\}\},$$

(3) $$\mu\delta U_{yH} = \max\{0, \min\{1, \frac{U - 1{,}05U_n}{0{,}05U_n}\}\},$$

where: $\mu\delta U_{yL}$, $\mu\delta U_{yN}$, $\mu\delta U_{yH}$ - respectively, a function of belonging to indicators of established normal, low, and high voltage, U – voltage, U_n – nominal voltage.

The term set for the fuzzy variable "Phase B" is written similarly to "Phase A" and the set Tu={"UBlow", "UBmid", "UBhigh"} is used. And similarly, the term set for the fuzzy variable "Phase C" is written, where the set Tu={"USlow", "USmid", "UShigh"} is used. That is, the sets UAlow, UBlow, UClow are a function of membership of established deviation indicators, which describe a low degree of deviation from the requirements of norms and standards. The sets UAmid, UBmid, UClmid are the nominal values of the voltage deviation, which are built on the basis of the requirements of the IEEE standard and DSTU [2].

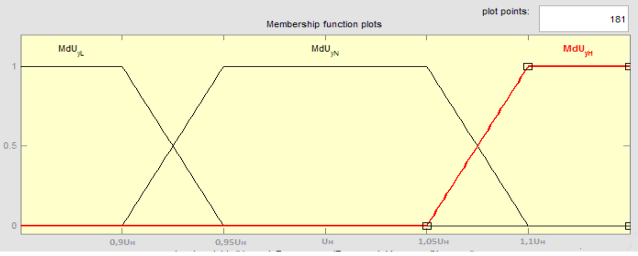

Fig.1. The function of belonging to the steady state voltage indicators

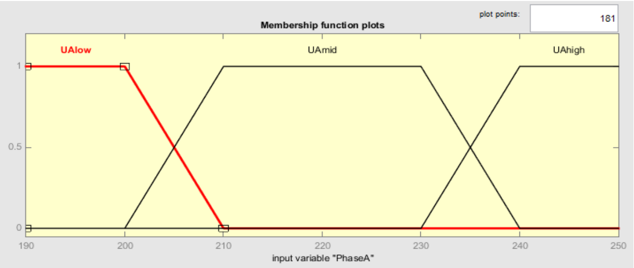

Fig.2. Membership function for the terms of the input variable "Phase A"

The sets UAhigh, UBhigh, UChigh are a function of membership of established deviation indicators, which describe a high degree of deviation from the requirements of norms and standards. The specified norms regulate both permissible and maximally permissible steady-state voltage deviation, which is convenient for describing the function of membership of therms in a trapezoidal form. In fact, the membership function of the term "UAmid" corresponds to the vague concept of "the degree of voltage satisfaction with this quality norm", and "UAlow", "UAhigh" characterize the degree of voltage deviation from the norm. And the set Tp={"OLTCDmin", "OLTCDmax"}, (as an example below - Fig. 3).

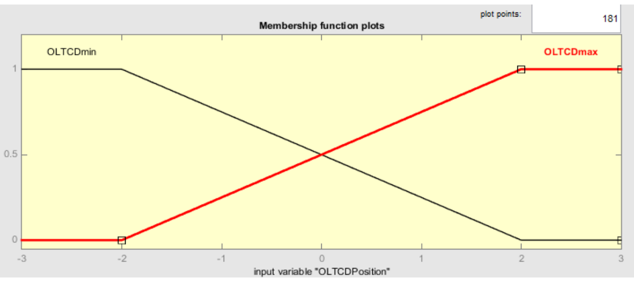

Fig.3. Membership function for the terms of the input variable "Position of the tap-changer device"

At the same time, each of the terms of the first three input variables is evaluated on a scale from 190 V to 250 V, and the fourth input variable is evaluated on a scale from -3 to +3 operating modes of switching the device. The set Tn={"OLTCD-", "OLTCD+"}, (as an example below - Fig. 4(a)) and is evaluated on a scale from -2 to +2 switching modes of the device. Where the following linguistic usage is involved: increase (+), decrease (-), do not change (0), i.e. "OLTCD-" - decrease, "OLTCD+" - increase, and "0" - remains in place without change. The term set for the fuzzy output variable "Disabling a part of the load" uses the set To={"DISABLE PARTS OF THE LOAD"}, (as an example below - Fig. 4(b)) and is estimated on a scale from 0 to 200 kW. In the same way, a term set is created for the fuzzy output variable "Inclusion of additional load", the set Tv={"ON load"} is used (as an example below - Fig. 4(c)) and is similarly rated on a scale from 200 kW to 600 kW. And for the term set for the fuzzy output variable "Turning on the AVD device" the set Td={"ON.AVD"} (as an example below - Fig. 4(d)) and is rated on a scale from 0 V to 500 V.

Heuristic knowledge of this problem area of logic inference for normalization of the steady-state voltage deviation is given in the rules of logic inference (some of the rules are presented):

1) if UAlow and OLTCDmax → OLTCD+;
2) if UBlow and OLTCDmax → OLTCD+;
3) if UClow and OLTCDmax → OLTCD+;
4) if UAhigh and OLTCDmin → OLTCD-;
5) if UBhigh and OLTCDmin → OLTCD-;
6) if UChigh and OLTCDmin → OLTCD-;
7) if UAhigh and OLTCDmin → ON load;
8) if UBhigh and OLTCDmin → ON load;
9) if UChigh and OLTCDmin → ON load;
10) if UAlow and UBhigh and UClow → ON AVD;
11) if UAlow and UBlow and UChigh → ON AVD;
12) if UAhigh and UBhigh and UClow → ON AVD;
13) if UAhigh and UBlow and UChigh → ON AVD;
14) if UAmid and UBlow and UChigh → ON AVD;
15) if UAlow and UBmid and UChigh → ON AVD;
16) if UAhigh and UBlow and UCmid → ON AVD;
17) if UAlow and UBhigh and UCmid → ON AVD;
18) if UAmid and UBhigh and UClow → ON AVD;
19) if UAhigh and UBmid and UClow → ON AVD;
20) if UAmid and UBmid and UClow → ON AVD;
21) if UAmid and UBlow and UChigh → ON AVD;
22) if UAmid and UBlow and UCmid → ON AVD;
23) if UAmid and UBhigh and UCmid → ON AVD;
24) if UAlow and UBmid and UCmid → ON AVD;
25) if UAhigh and UBmid and UCmid → ON AVD;

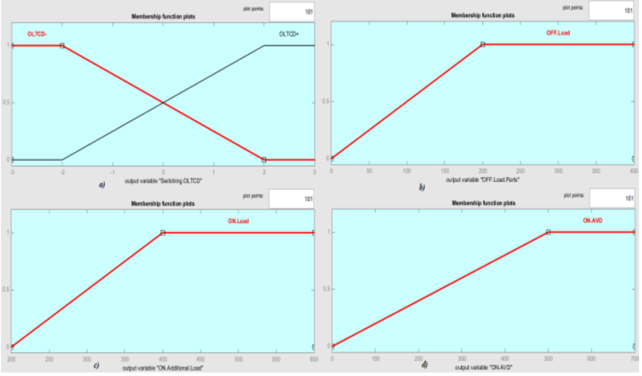

Fig.4. The accessory function for the terms of the output variables: a) - "Switching the tap-changer device"; b) - "Disconnecting part of the load"; c) – "Inclusion of additional load"; d) - "Enabling the AVD"

Results and discussion

After applying the rules of fuzzy derivation, we get the result for specific values of the input variables. After changing the values of the input variables, the results of the performed measurements are considered. Since the process of fuzzy modeling involves the analysis of the results of fuzzy derivation at different values of the input variables in order to establish the adequacy of the developed fuzzy model, the following cases were developed and considered. Let's consider the rule of logical deduction for normalization of the steady voltage deviation in one of the phases "Phase A", "Phase B" or "Phase C" (as an example below - Fig. 5), where the voltage is low, and the position of the on-load tap-changer device is not set to the maximum. This rule was given from above and in its full form has the following form: if (UAlow or UBlow or UClow) and not OLTCDmax → OLTCD+. In Fig. 5 in the first rule, the values of "Phase A" are given for the low voltage position, that is, "Phase A" has a value of 191 V, in the given rules of the logical output it looks like "UAlow", and at this moment the phases "Phase B" and "Phase C" correspond to the nominal voltage value of 220 V ("UBmid", "UCmin"). "On-load tap-changer device position" is not set to the maximum position (OLTCDmax) and has a value of "-1.98", and therefore the developed fuzzy output system recommends switching the tap-changer to position 1 [13, 14].

In a similar way, we consider the rule of logical deduction for normalization of the steady voltage deviation in one of the phases "Phase A", "Phase B" or "Phase C" (as an example below - Fig. 6), where the voltage is high, and the position of the on-load tap-changer device is not set to the minimum [15, 16]. This rule in its full form has the following form: if (UAhigh or UBhigh or UChigh) and not OLTCDmin → OLTCD-.

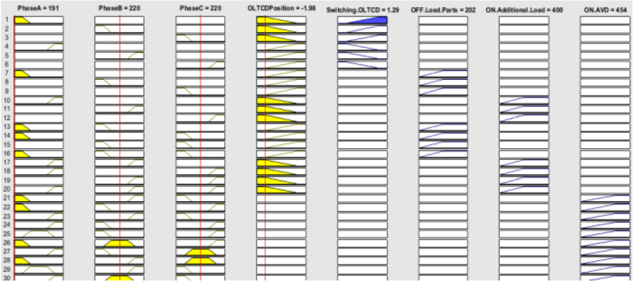

Fig.5. The rule of logical deduction when reducing the voltage of one of the three phases when the on-load tap-changer is not at maximum

In Fig. 6 in the 5th rule, the values of "Phase B" are given to the high voltage position, that is, "Phase B" has a value of 247 V, in the given rules of the logic output it looks like "UBhigh", and at this moment the phases "Phase A" and "Phase C" correspond to the nominal voltage value of 220V ("UAmid", "UCmin"). "On-load tap-changer device position" is not set to the minimum position (OLTCDmin) and has a value of "2.06", and therefore the developed fuzzy output system recommends switching the on-load tap-changer to the -1 position.

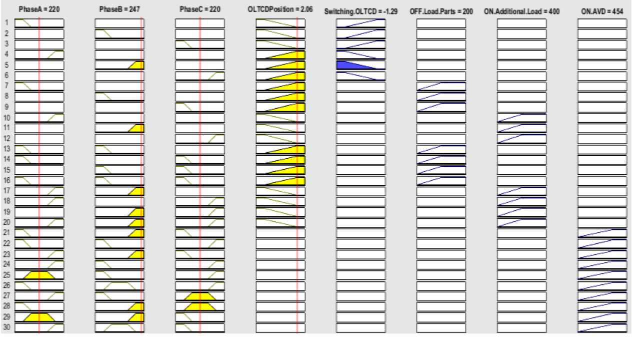

Fig.6. The rule of logical conclusion with an increased voltage of one of the three phases when the on-load tap-changer is not at a minimum

Consider such a case, (as an example below - Fig. 7), in the 7th rule, where with the entered values of the phases "Phase A" is at the low voltage position "192 V" (UAlow), and at this time "Phase B" and "Phase C" correspond to the nominal voltage value of 220 V (UBmid, UCmid), and the "On-load tap-changer device Position" is already at the maximum (OLTCDmax), and has a value of "2.48", and therefore the developed fuzzy output system recommends to disconnect part of the load to the value of 245 kV. The rule of logical deduction in its full form has the following form: if (UAlow or UBlow or UClow) and OLTCDmax → OFF. Parts of the Load.

Likewise, consider a similar case, (as an example below - Fig. 8), in the 11th rule, where with the entered phase values "Phase B" is at the high voltage position "246 V" (UBhigh), and at this time "Phase A" and "Phase C" correspond to the nominal voltage value of 220 V (UBmid, UCmid), and the "Tap-tap device position" is already at the minimum (OLTCDmin), and has the value "-2.41", and therefore the developed fuzzy output system recommends to include the additional load to the value of 245 kV. The logic output rule in its full form has the following form: if (UAhigh or UBhigh or UChigh) and OLTCDmin → ON load.

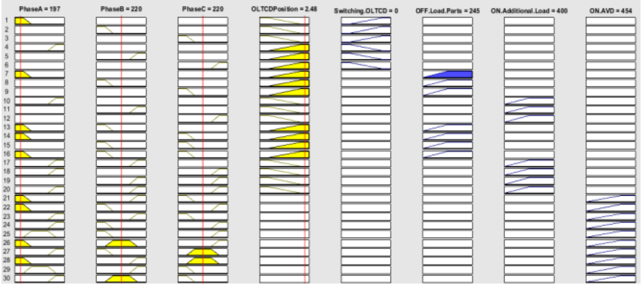

Fig.7. The rule of logical deduction at a reduced voltage of one of the three phases when the on-load tap-changer is operating at the maximum

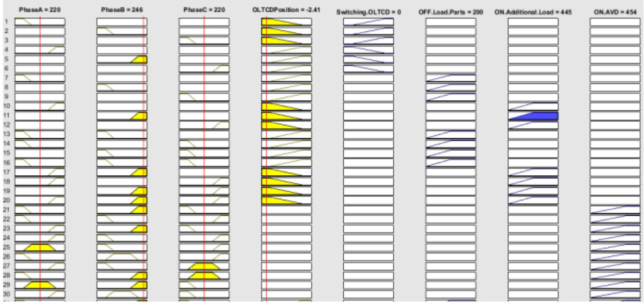

Fig.8. The rule of logical conclusion with an increased voltage of one of the three phases when the on-load tap-changer is operating at a minimum

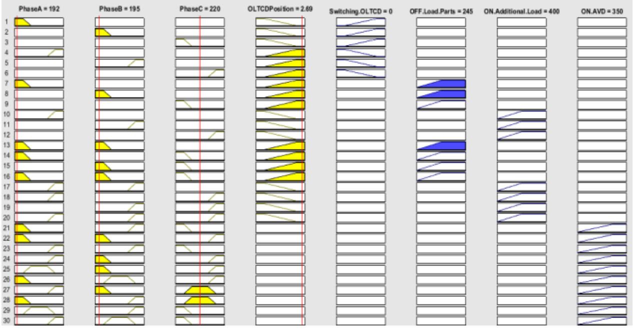

Fig.9. The rule of the logical conclusion at the reduced voltage of two phases and one phase with the nominal voltage when the on-load tap-changer operates at the maximum

The next case in Fig. 9 in the 13th rule, where with the entered phase values "Phase A" is at the low voltage position "192 V" (UAlow) and also "Phase B" is at the low voltage position "195 V" (UBlow), and in this time "Phase C" correspond to the nominal voltage value of 220V (UCmid), and "Position of the tap-changer device" is already at the maximum (OLTCDmax) and has the value "2.69", and therefore the developed fuzzy output system recommends to disconnect part of the load to the value " 245 kV". The rule of the logical conclusion in its full form has the following form: if (UAlow or UBlow or UClow) and (UAlow or UBlow or UClow) and OLTCDmax → OFF. Parts of the Load.

The next case in Fig. 10 in the 17th rule, where with the entered values of the phases "Phase A" is at the high voltage position "247 V" (UAhigh) and also "Phase B" is at the high voltage position "245 V" (UBhigh), and in this time "Phase C" corresponds to the nominal voltage value of 220V (UCmid), and the "Position of the tap-changer device" is already at the minimum (OLTCDmin) and has the value "-2.41", and therefore the developed fuzzy output system recommends including an additional load to the value "445 kV". The rule of logical conclusion in its full form has the following form: if (UAhigh or UBhigh or UChigh) and (UAhigh or UBhigh or UChigh) and OLTCDmin ON load.

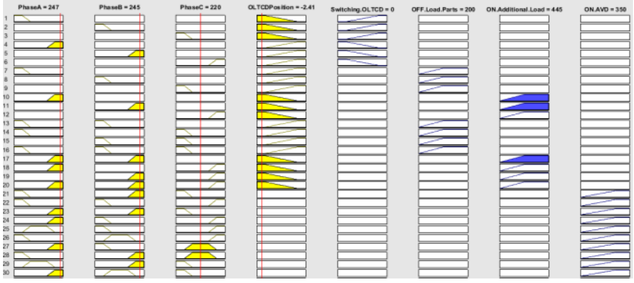

Fig.10. The rule of logical conclusion with increased voltage of two phases and one phase with nominal voltage when the on-load tap-changer is operating at a minimum

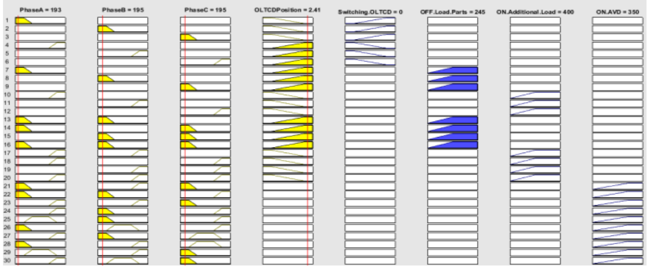

Fig.11. The rule of logical deduction at reduced voltage of three phases at the same time and when the on-load tap-changer is operating at maximum

In Fig. 11 in the 7th, 8th, 9th, 13th, 14th, 15th and 16th rules, where with the entered values of the phases "Phase A" is at the low voltage position "193 V" (UAlow), "Phase B" is at the low voltage position "195 V" (UBlow) and "Phase C" is also at the low voltage position "195 V" (UClow), and "On-load tap-changer device position" is already at the maximum (OLTCDmax), and has a value of "2.41", and therefore, the developed fuzzy output system recommends disconnecting part of the load to the value of "245 kV". The rule of logical conclusion in its full form has the following form: if UAlow and UBlow and UClow and OLTCDmax → OFF. Parts of the Load.

Similarly, in Fig. 12 in the 10,11,12,17,18,19,20th rules, where with the entered values of the phases "Phase A" is at the high voltage position "246 V" (UAhigh), "Phase B" is at the high voltage position "243 V" (UBhigh) and "Phase C" is also at the high voltage position "240 V" (UChigh), and "Position of the tap-changer device" is already at the minimum (OLTCDmin), and has the value "-2.55", and therefore the developed fuzzy inference system recommends including the additional load to the value of "445 kV". The rule of the logical conclusion in its full form has the following form: if UAhigh and UBhigh and UChigh and OLTCDmin → ON load.

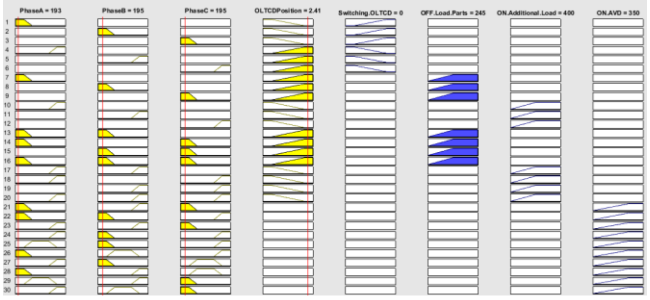

Fig.12. The rule of logic inference with the increased voltage of three phases at the same time and when the on-load tap-changer is operating at a minimum

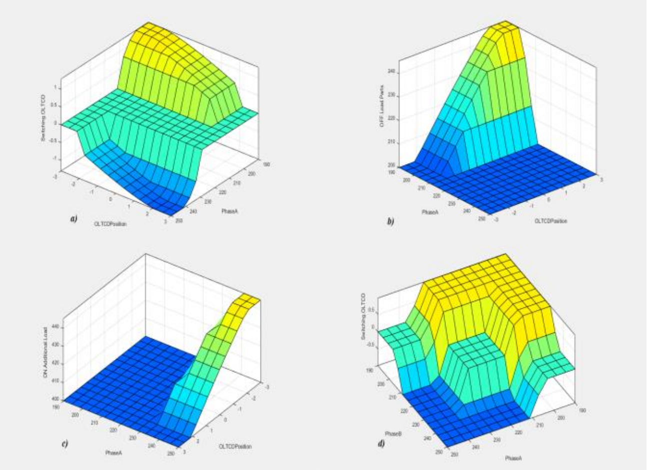

Fig.13. Graphical interface for viewing the fuzzy output surface for: a) Switching of the "OLTCD" device; b) Disconnection of part of the load; c) Inclusion of additional load; d) Turning on the "AVD" device

The graphical interface for viewing the fuzzy output surface (as an example below - Fig. 13). The figure shows that when the voltage on one of the three phases changes, the on-load tap-changer will switch to the desired position. When the voltage on two phases changes, an additional load will be switched on or a part of the load will be switched off. And when the voltage on all three phases changes, the additional voltage device will be turned on. In some cases, when the voltage on two or three phases changes and the on-load tap-changer device operates, the additional voltage device and the additional load are turned on at the same time, but in some cases, part of the load is turned off. This analysis helps to establish accurate voltage regulation in one phase, or on all three phases of the network at the same time. After varying the input variable values, the adequacy of this developed fuzzy model is determined. This model is effective because the control command can be issued not on the fact of violation of the norms of voltage deviation and quality of electric energy, but in advance, since the membership functions of term-sets intersect.

Conclusions

The use of a control algorithm based on fuzzy logic makes it possible to increase the efficiency of tap-changer and additional voltage devices in regulating the established voltage deviation, compared to existing systems. The proposed algorithm is quite simple to implement on programmable logic controllers or fuzzy controllers, it can be easily supplemented or changed when adapting to specific operating conditions.

The scientific novelty of the work consists in the improvement of the model of regulation of electric energy quality indicators based on the method of fuzzy logic. When obtaining models of automated regulation of the quality of electrical energy, methods of data processing and analysis were applied, which allowed: to output and see input and output data, places of voltage losses in the network, which affect the quality of electrical energy; and this made it possible to increase the adequacy of power consumption quality regulation models. The relationship between the efficiency of processing and analysis of input and output data and the automated regulation of the quality of electricity consumption was analytically established, which made it possible to conduct a comparative analysis of the models of processing and analysis of voltage data in distribution networks with models obtained by other methods.

The practical significance of the work is as follows: the built model using the method of fuzzy logic allows to speed up the matching of the transformer with the on-load tap-changer to the control circuit and establish a more accurate voltage regulation, which will increase the efficiency of the transformer and the system itself; the results of the work can be used in the design of the substation for introduction into the power system.

Prospects for the author's further research may be directed to the development of structural and principle control schemes for tap-changer transformers and the creation of FPGA models for the implementation of more detailed integer calculations.

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