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# METHOD AND ALGORITHM OF FUZZY CONTROL OF REACTIVE CAPACITY AND VOLTAGE PROVIDING REGIME RELIABILITY OF ELECTRIC NETWORKS

Guliyev H.B.

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Azerbaijan Scientific-Research
and Design-Prospecting Power Engineering Institute
AZ1012, Ave. H.Zardabi- 94
E-mail: huseyngulu@mail.ru

**Abstract**

*The structure and algorithm of the voltage and reactive power control system for distribution networks with on site power sources containing fuzzy logic controller (FLC) is presented. The controlling parameters are: the transformers voltage ratio and capacities of the reactive power sources in distribution networks. The placement of reactive power sources, their values and also transformers regulator's positions are determined using traditional methods of optimization for selected networks. The structure of reactive power sources and transformers voltage ratio control system containing the fuzzy logic controller is presented in this paper. The problem of optimal correction of transformers voltage ratio and power sources at time of their deviation from the preset values to minimize losses in studied network and maintaining of nodes voltages on the necessary level is considered. The algorithm of membership function formation for input variables of FLC to control / correct capacitors value is shown. Modeling results for real electrical circuit, reactive capacity correction in nodes and transformers impact on losses and voltage profile in studied network are presented.*

**Key words:** voltage, reactive power, fuzzy logic, power losses, optimal placement of static capacitor, controller, membership function, electric network.

## I. Introduction

For mode profitability conditions and voltage quality support in distributive electric networks the adjustable batteries of static capacitors and voltage control units for transformers under loading regulation are used. Among voltage and reactive power regulating devices the automatic excitation regulators for local sources (synchronous generators, diesel or gas-turbine units) in distributed generation networks also are used.

The choice of a placement position and static condensers batteries rate planned for installation is the optimizing problem which essence consists of total active power losses minimization. Now methods of nonlinear optimization [1-5] and also heuristic methods are applied to the decision of the given problem [6].

With help of [1-6] methods for planned schemes and predicted modes the batteries of static condensers optimum rates assumed for installation in network knots are defined. In real operation conditions the loadings consumption capacity in a network continuously changes, that leads to a deviation of a current production schedule from planned on the set period (days, weeks etc.). Actual values of reactive power in network knots will differ from optimum chosen values for their covering of condenser units capacities. The losses levels and knots voltages will change according to current mode changes in a network. Such current losses values and voltages will differ from their corresponding values in optimum modes.

The difference between current knot's reactive power value and optimum chosen capacity of the condenser battery is possible to compensate operatively by change of minimum share of capacity correction pre-setted in knot in a direction of losses reduction in a network.

The power factor correction condensers module usually consists of several separate elements or groups of elements, everyone with own contactor or switch. Reactive power covering demand and a power factor are continuously estimated and the condenser modules connected and disconnected necessarily for optimum level achievement.

The algorithm of indistinct logic realized in block of current mode condition estimation in distributed generation (DG) network is developed for definition of optimum number of modules in each knot. In the same block the necessity of planned parameters values updating - rates of condensers capacities installed in controllable knots and transformer's voltage ratio is checked.

The problem solution on definition of necessity of connected condenser's capacity rate correction and a choice of transformer's voltage ratio is spent by developed indistinct system's algorithm in which as inputs the knots voltages and power losses indicators are defined. Thus necessity of condenser correction for this or that knot will be defined by an importance indicator of condenser's capacity variability. Necessity of correction of condenser's capacity for this or that knot is defined in case of large value of this indicator.

For practical correction of condenser's capacity value in knots of installation the indistinct logic regulator is used.

## II. Structure of Reactive Power and Voltage Control System in Distributed Generation Networks

In dispatching management modern practice the operative modes correction in power system electric networks has a great value at control solutions acceptance at a network mode deviation on $Q$ and $U$ from their values received on the base of optimum modes calculation. Thus for a choice of correcting actions for reactive power and voltage (RCV) management the criterion of a minimum of losses is used at performance of preservation conditions of the standard deviation of knots voltages [2,3,7-9]. RCV control in distribution networks basically is carried out by means of batteries of static condensers (BSC), and also generating sources, placing in a network for a local loads covering and transformers regulated under loading. The choice of adjustable static condensers batteries number and generating sources, their placing in network is an optimizing problem. The decision of given problem for electric network normal scheme defines the optimum number of regulating devices.

At an operational control in process of scheme and mode change current optimum values of voltage in knots $U_{i,max}$ and total losses values in network $\Delta P_{i,min}$. are defined. In accordance with calculated new values $U_{i,max}$, $\Delta P_{i,min}$ the setting of numbers of individual condensers $K_{конд,i}$ for knots in which their installation is accepted, and transformers regulating devices positions $K_{t,i.}$ are defined.

Such optimizing calculations can be executed in frame of the program complex for power system condition estimation. Algorithms used by these programs are known [10-15] and basically consist in periodic optimizing calculations carrying out according to a current scheme condition and a system mode. On the basis of current optimizing calculations results comparison - knots voltages values and total losses in a network, with the optimum values established for base normal modes, necessity of condensers batteries capacities $(C_{ki})$ correction, transformers voltage ratio for remote adjustable transformers, voltages of generators placed in distributed generation system is defined. Depending on a deviation value of current optimum values of the voltage in controllable knots and network losses value from their corresponding values in nominal base mode the operating influences sizes for condenser batteries modules established in controllable knots switching on and positions of transformers regulating device are defined.

Following the above-stated distributed network reactive power control mode it is possible to present the general control scheme in form of the following block structure of the static condensers batteries, position of transformers switching and synchronous generators voltages co-ordinate control.

The general management concept for the purpose of optimum mode support in an electric network with the distributed generation consists in a choice of static condensers capacity from among the set condensers in knots, and also in transformer voltage ratio definition installed in connection point of DG network with a power system and its switching to position providing a minimum of power losses in a network. Necessity of correcting actions on condensers and the transformer arises at deviations of network current mode losses from their (planned) values calculated for network optimum modes.

In considered statement correcting control influence on change of condensers batteries modules in network knots and transformers voltage ratio accepted in form of linear dependence on a deviation of current conditions (changes of active and reactive power of knots loadings) [16]:

$$\Delta Y = f(k, \Delta d) \tag{1}$$

where $\Delta Y = \overline{Y} - Y$, $\Delta d = \overline{d} - d$

$\overline{Y}$, $\bar{d}$ – planned values of adjustable and initial data

$$\overline{Y} = \begin{Vmatrix} C_{ki} \\ \cdot \\ K_{ti} \end{Vmatrix}, \qquad d = \begin{Vmatrix} P_1 + jQ_1 \\ \cdot \\ P_i + jQ_i \end{Vmatrix}, \qquad i = 1 \ldots n$$

$\Delta Y$ – operating influences on change of condenser capacity rate on $\Delta C_{k,i}$ and change of adjustable transformer's voltage ratio $\Delta K_{t,i}$; $\Delta d$ – initial data changes of knot loadings $\Delta P_i + j\Delta Q_i$.

Condensers and transformers control equation adjusting parameters are defined from optimization conditions:

$$\min_{k,\ \Delta P_i,\ \Delta Q_i} M\,\Delta P(\overline{Y} + f(k, \Delta d), x, d) \tag{2}$$

where $x$ - dependent parameters:

$$x = \begin{Vmatrix} U_1 \\ \cdot \\ \cdot \\ U_n \end{Vmatrix}, \quad i = 1...n$$ - knots voltages vector.

## III. Correction of DG Network Mode Parameters by a Fuzzy Logic Method

The probabilistic and indistinct-defined character of scheme and network mode parameters variability (knots power and voltage) and also the electric systems modes (ESM) models nonlinearity, its parametrical uncertainty and unpredictability complicates application of the known determined methods for active and reactive power flows control in RG network. For the problem solution in choice of correcting control in [12, 14, 17-20] the algorithms – as solving rules generated on the base of linear dependences in form of (1) are used. Besides, for correcting values for $C_{k,i}$ and $K_{t,j}$ an estimation of the determined active power losses equivalent is defined. But even in this case the problem becomes complicated when operating vector "$\overline{Y}$"$\cdot$ dimension increases.

In frame of indistinct system the correcting actions choice on sizes of knots capacities and transformers voltage ratio is formalized on base of linguistic rules defined by membership functions. The purpose of reactive power flow mode correction adds up to the "max-min" problem solution [9,10].

For a problem of correcting action definition on change of installed in knots condensers rate a resultant membership function of an admissibility of condenser rate $\mu_{S_C}(i)$ correction in $i$ mode and at *k* accepted rules:

$$\mu_{S_C}(i) = \max k\,[\min[\mu_P(i),\ \mu_U(i)]] \tag{3}$$

where $\mu_P(i),\ \mu_U(i)$ membership functions of power losses and voltage indicators.

From the determined optimizing problem solution with taking into account the forecast of initial data:

$$\overline{d} = \left|\overline{\pi}, \overline{P}_{H,i}, \overline{Q}_{H,i}\right|$$

The planned targets for capacities rates in knots and values ratio of adjustable transformers are defined as:

$$\overline{Y} = \left|C_{k,1}, C_{k,2}, \cdots, C_{k,n}, K_{t,1}, K_{t,2}, \cdots, K_{t,m}\right|$$

where, $\overline{\pi}$ - active power losses; $\overline{P}_{H,i}$, $\overline{Q}_{H,i}$ - predictably values of active both reactive power in the *i*- th loading knot.

In frame of the is indistinct-defined statement the problem solution of an estimation of a share of correcting action on condenser batteries rate change in knots and position of the transformers regulating devices, can be realized in the form of following stages:

1. To define total active power losses for DG system base structure (are carried out on the base of flow distribution calculation programs). The program complex ETAP which provides steady stage calculations, and also calculations of Q sources optimum placement in a network is used in

this research.

2. By change of a reactive power compensation share in each knot to carry out the flow distribution calculations and define the total active power losses in each case $\Delta C_{k,i.}$.

3. To calculate losses decreasing indicators as:

$$\Pi_{\Delta P}(i) = \frac{(\Delta P(i) - \Delta P_{min})}{(\Delta P_{max} - \Delta P_{min})} \tag{4}$$

Where $i$=2, 3, … n - number of knots in which batteries of condensers are placed.

By indicator value (4) the capacity correction suitability for knot "i" is defined. If this indicator is highest for any $i$ th knot the capacity correction in this knot is most comprehensible.

4. The membership functions for power losses indicators $\mu(L_{\Delta P})$ and voltages in each knot $\mu_U(\mathrm{i})$ are accepted as model (3) inputs.

5. Indistinct model's (3) target parameter - a resultant membership function $\mu_{S_c}(\mathrm{i})$ defines an acceptability of capacity correction in the given knot.

$$\tilde{Y} = \tilde{U} \circ \tilde{\Pi}_{\Delta P} \circ R(U, L_{\Delta P}, Y) \tag{5}$$

Where, «∘» -the "мах-мin" composition's symbol; R - the indistinct relation.

6. Dephasification of an indistinct control output signal for $C_{k,i}$ condensers batteries capacity and transformers voltage ratio $K_{t,i}$ correction:

$$Y = F^{-1}[\tilde{Y}] \tag{6}$$

where,

$$\tilde{Y} = \max\{\min[\mu_P(\mathrm{i}),\ \mu_U(\mathrm{i})]\}$$

F –the phasing symbol.

According to the offered algorithm for network knot definition in which it would be preferable the battery of static condensers capacity correction, in the indistinct logic regulator the knots voltages and losses index (IL) $\Pi_{\Delta P}(\mathrm{i})$ calculated on (4) are accepted as input parameters. The higher limiting value for $\Pi_{\Delta P}(\mathrm{i})$ for i knot is considered as the priority knot in which it is necessary to carry out the correction established in knot where the condensers battery was connected.

Indistinct variable of knots voltages, losses indexes $\Pi_{\Delta P}(\mathrm{i})$, and also an indicator of network knot preference in which the condensers battery will be corrected, are described in terms of indistinct definitions: Critical Low, Low, Low-Medium, Medium, High-Medium and High.

Subsets fuzzy logic $A_{1i}$ of an indicator of loss of capacity on terms to linguistic variables it is resulted below:

$A_{11} = CL$ (Critical Low) $\triangleq (p, \mu_{11}(p))$

$A_{12} = L$ (Low) $\triangleq (p, \mu_{12}(p))$

$A_{13} = LM$ (Low-Medium) $\triangleq (p, \mu_{13}(p))$

$A_{14} = M$ (Medium) $\triangleq (p, \mu_{14}(p))$

$A_{15} = HM$ (High-Medium) $\triangleq (p, \mu_{15}(p))$

$A_{16} = H$ (High) $\underline{\underline{\Delta}}(p, \mu_{16}(p))$

Defined $A_1$ a universum of a subset of fuzzy-ligic sets the generalised kind it is possible to write a below-mentioned variant

$$\underline{\underline{\Delta}}(p, \mu(p)) = \sum_{p \in A_1} \mu_{1i}(p_i)) / p_i \quad , \forall p_i \in A_1$$

Subsets fuzzy logic $A_{2j}$ of an indicator of voltage knots on terms to linguistic variables it is resulted analogycaly below:

$A_{21} = CL$ (Critical Low) $\underline{\underline{\Delta}}(V, \mu_{21}(V))$

$A_{22} = L$ (Low) $\underline{\underline{\Delta}}(V, \mu_{22}(V))$

$A_{23} = LM$ (Low-Medium) $\underline{\underline{\Delta}}(V, \mu_{23}(V))$

$A_{24} = M$ (Medium) $\underline{\underline{\Delta}}(V, \mu_{24}(V))$

$A_{25} = HM$ (High-Medium) $\underline{\underline{\Delta}}(V, \mu_{25}(V))$

$A_{26} = H$ (High) $\underline{\underline{\Delta}}(V, \mu_{26}(V))$

But, defined $A_2$ a universum of a subset of fuzzy-ligic sets the generalised kind it is possible to write a below-mentioned variant

$$\underline{\underline{\Delta}}(V, \mu_{2j}(V)) = \sum_{V \in A_2} \mu_{2j}(V_j) / V_j \ , \quad \forall V_j \in A_2$$

In Tables 1 and 2 the membership functions for the above-stated indistinct linguistic variables are presented.

Table 1

The membership functions for losses and voltage indicators

| Description of variables | Critical Low | Low | Low-Medium | Medium | High-Medium | High |
|---|---|---|---|---|---|---|
| Indicators of capacity losses | < 0,15 | 0 – 0,25 | 0,12 – 0,5 | 0,32 – 0,75 | 0,5 – 1,0 | >0,75 |
| Voltages | < 0,92 | 0,9 – 0,94 | 0,91 – 0,96 | 0,95 – 1,0 | 0,98 – 1,05 | 1,02 – 1,1 |

Table 2

The membership functions of an indicator of correction preference (ICP)
for condensers battery capacity in network knots

| Variable | Critical Low | Low | Low-Medium | Medium | High-Medium | High |
|---|---|---|---|---|---|---|
| ICP(*i*) | <0,15 | 0 – 0,25 | 0,12 – 0,5 | 0,32 – 0,75 | 0,5 – 1,0 | ≥0,75 |

For of network knot definition with the revealed preference of connected condensers battery's capacity correction it is necessary to calculate the losses and voltage indicators for each knot, and then to present each of them as they own membership functions. Using the values of knot's voltages and losses indicators $L_{\Delta P}(\mathrm{i})$ the rules in form of the indistinct logic conclusions set matrix are formulated and generalized in Table. 3: CL-Critical Low; L- Low; LM- Lw - Medium; M-Medium; HM- High- Medium; H- High;

Table 3

Matrix of solutions for knot definition in which the condensers battery capacity correction is preferable

| **Parameters** | | **Voltage in knots** | | | | | |
|---|---|---|---|---|---|---|---|
| | | CL | L | LM | M | HM | M |
| $L_{\Delta P}$ (i) | CL | L | L | L | L | L | L |
| | L | L | L | L | L | LM | LM |
| | LM | L | L | L | LM | LM | M |
| | M | L | L | L | LM | M | HM |
| | HM | L | L | LM | M | HM | H |
| | H | L | LM | LM | M | HM | H |

## IV. The Results of Modeling

The application of indistinct regulator algorithm is reviewed on an example of one of IEEE 30 BUS electric network. Investigated network contains 30 knots. With use of ETAP program complex for the given network depending on knots loading the optimum points (network knots) for condensers batteries placing and treir capacity rates are defined. The knots voltages, power factors, quantity and capacity of placed batteries, and also the total expenses necessary for condensers installation and operation are defined for three various loading modes. Calculations results are presented in Table 4-6.

Table 4

Calculation results of condensers batteries optimum distribution at 70 %loading

| Knot name | $U_{calc}$ в % | $\cos\varphi$ | Information about BSC | | | Total cost (thousand $) |
|---|---|---|---|---|---|---|
| | | | кVAR/sect. | No of sect. | Total cap кVAR | |
| Bus1 | 100,0 | 0,858 | 1000 | 3 | 3000 | 122,4 |
| Bus2 | 99,2 | 1,0 | 1000 | 3 | 3000 | 122,4 |
| Bus3 | 99,2 | 0,997 | 1000 | 1 | 1000 | 41,6 |
| Bus4 | 97,8 | 0,644 | 1000 | 3 | 3000 | 122,4 |
| Bus5 | 97,6 | 0,999 | 1000 | 2 | 2000 | 82,0 |
| Bus6 | 97,0 | 0,78 | 1000 | 3 | 3000 | 122,4 |
| Bus7 | 97,3 | 1,0 | 1000 | 3 | 3000 | 122,4 |
| Bus8 | 96,7 | 1,0 | 1000 | 3 | 3000 | 122,4 |
| Bus9 | 96,9 | 0,998 | 1000 | 3 | 3000 | 122,4 |
| Bus10 | 97,8 | 0,494 | 1000 | 3 | 3000 | 122,4 |
| Bus11 | 96,5 | 1,0 | 1000 | 1 | 1000 | 41,6 |
| Bus12 | 97,8 | 0,994 | 1000 | 3 | 3000 | 122,4 |
| Bus13 | 96,3 | 0,997 | 1000 | 1 | 1000 | 41,6 |
| Bus14 | 97,4 | 0,998 | 1000 | 3 | 3000 | 122,4 |
| Bus15 | 96,1 | 0,968 | 1000 | 1 | 1000 | 41,6 |
| Bus16 | 98,7 | 0,934 | 1000 | 2 | 2000 | 82,0 |
| Bus17 | 101,7 | 0,90 | 1000 | 3 | 3000 | 122,4 |
| Bus18 | 99,5 | 1,0 | 1000 | 2 | 2000 | 82,0 |
| Bus19 | 98,1 | 0,992 | 1000 | 2 | 2000 | 82,0 |
| In total: | - | - | - | 45 | 45000 | 1840,8 |

Table 5

Calculation results of condensers batteries optimum distribution at 85 %loading

| Knot name | $U_{calc}$ в % | $\cos\varphi$ | Information about BSC | | | Total cost (thousand $) |
|---|---|---|---|---|---|---|
| | | | кVAR/sections | No of sections | Total capacity кVAR | |
| Bus1 | 104,6 | 0,993 | 1000 | 3 | 3000 | 122,4 |
| Bus2 | 104,3 | 0,941 | 1000 | 7 | 7000 | 284,0 |
| Bus3 | 104,2 | 0,889 | | | | |
| Bus4 | 104,1 | 0,958 | 1000 | 4 | 4000 | 162,8 |
| Bus5 | 103,5 | 0,999 | 1000 | 1 | 1000 | 41,6 |
| Bus6 | 103,4 | 0,992 | 1000 | 6 | 6000 | 243,6 |
| Bus7 | 103,7 | 1,0 | 1000 | 1 | 1000 | 41,6 |
| Bus8 | 103,8 | 0,971 | 1000 | 9 | 9000 | 364,8 |
| Bus9 | 103,9 | 1,0 | 1000 | 2 | 2000 | 82,0 |
| Bus10 | 103,4 | 0,968 | 1000 | 1 | 1000 | 41,6 |
| Bus11 | 103,2 | 0,999 | 1000 | 5 | 5000 | 203,2 |
| Bus12 | 103,9 | 1,0 | 1000 | 1 | 1000 | 41,6 |
| Bus13 | 101,9 | 0,914 | 1000 | 1 | 1000 | 41,6 |
| Bus14 | 104,3 | 0,926 | 1000 | 5 | 5000 | 203,2 |
| Bus15 | 102,5 | 0,999 | 1000 | 2 | 2000 | 82,0 |
| Bus16 | 105,1 | 1,0 | 1000 | 11 | 11000 | 445,6 |
| Bus17 | 105,5 | 0,91 | 1000 | 3 | 3000 | 122,4 |
| Bus18 | 104,3 | 1,0 | 1000 | 2 | 2000 | 82,0 |
| Bus19 | 104.7 | 0,935 | 1000 | 3 | 3000 | 122,4 |
| In total: | - | - | - | 67 | 67000 | 2728,4 |

Table 6

Calculation results of condensers batteries optimum distribution at 100% loading

| Knot name | $U_{calc}$ в % | $\cos\varphi$ | Information about BSC | | | Total cost (thousand $) |
|---|---|---|---|---|---|---|
| | | | кVAR/sections | No of sections | Total capacity кVAR | |
| Bus1 | 104,7 | 0,904 | 1000 | 6 | 6000 | 243,6 |
| Bus2 | 104,0 | 1,0 | 1000 | 3 | 3000 | 122,4 |
| Bus3 | 104,1 | 0,958 | 1000 | 1 | 1000 | 41,6 |
| Bus4 | 104,0 | 0,989 | 1000 | 6 | 6000 | 243,6 |
| Bus5 | 103,8 | 0,984 | 1000 | 2 | 2000 | 82,0 |
| Bus6 | 103,8 | 0,92 | 1000 | 10 | 10000 | 405,2 |
| Bus7 | 103,9 | 1,0 | 1000 | 1 | 1000 | 41,6 |
| Bus8 | 103,4 | 0,933 | 1000 | 6 | 6000 | 243,6 |
| Bus9 | 103,6 | 1,0 | 1000 | 2 | 2000 | 82,0 |
| Bus10 | 103,4 | 0,966 | 1000 | 1 | 1000 | 41,6 |
| Bus11 | 103,5 | 0,948 | 1000 | 13 | 13000 | 526,4 |
| Bus12 | 104,6 | 1,0 | 1000 | 1 | 1000 | 41,6 |
| Bus13 | 102,0 | 0,836 | | | | |
| Bus14 | 105,8 | 0,925 | 1000 | 6 | 6000 | 243,6 |
| Bus15 | 104,0 | 0,999 | 1000 | 3 | 3000 | 122,4 |
| Bus16 | 106,2 | 1,0 | 1000 | 14 | 14000 | 566,8 |

| Knot name | $U_{calc}$ в % | cos $\varphi$ | Information about BSC | | | Total cost (thousand $) |
|---|---|---|---|---|---|---|
| | | | кVAR/sections | No of sections | Total capacity кVAR | |
| Bus17 | 105,2 | 0,831 | | | | |
| Bus18 | 104,7 | 1,0 | 1000 | 14 | 14000 | 566,8 |
| Bus19 | 104.4 | 0,958 | 1000 | 13 | 13000 | 526,4 |
| In total: | - | - | - | 102 | 102000 | 4141,2 |

As evident from Table 4, at 70 % of network loading on 19 knots the 45 sections of condensers batteries should run, at loading of 85 % on 18 knots – the 67 should run and at last, at 100 % to network loading on 17 knots – the 102 sections should run. Thus total capacities of sections of the condenser accordingly make 45,0 MVar, 67,0 MVar and 102,0 MVar, and total expenses 1840,8; 2728,4 and 4141,2 thousand US dollars. I.e. at loading reduction the optimum capacity of sections running concerning to initial mode has decreased for 34,0 %, and for the third mode on 56,0 %.

On Fig. 1 the profiles of voltage levels for bus 10 кV consumers of network district are shown at various modes. Apparently, in some knots the bus 10 кV voltage has decreased on 5 % average. It has been defined, that voltage reduction on consumer buses up to permissible level is connected not with condenser batteries placing, but with discrepancy of distributive network lines leghth.

The above calculations results analysis shows that depending on electric network modes for increasing of electric power distribution efficiency, the periodical correction, i.e. optimum condensers batteries capacity control in knots is necessary.

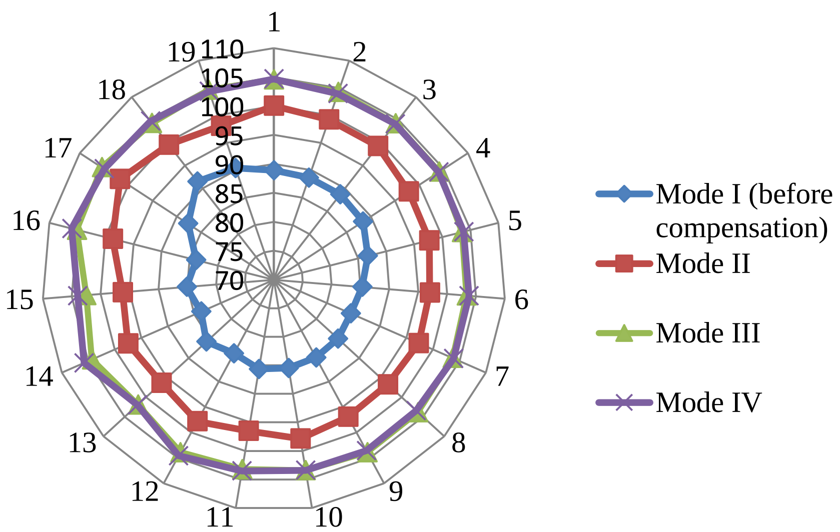


Fig. 1. Voltage profiles in 10 кV knots

## V. Conclusion

1. For optimum electric network mode correction the model of reactive power and voltages indistinct control is developed allowing improving the knots voltage values and reducing power losses.
2. An algorithm realizing the regulator indistinct logic principle is developed for condensers batteries capacity operative correction in knots by criterion of a network's mode optimality.
3. On the base of researches provided on an example of 30-knots IEEE network scheme, are established that the operative condensers batteries capacity correction on the by means of the

indistinct logic regulator allows to keep optimum conditions for DG mode at current loading deviations on network buses.

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