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SHUNT REACTORS CONTROL ALGORITHM USING FUZZY SETS THEORY

A.M. Hashimov A.R. Babayeva H.B. Guliyev

Azerbaijan Scientific-Research and Designed-Prospecting Institute of Energetics, Baku, Azerbaijan
ahashimov@azerenerji.gov.az, sunlite10@gmail.com, huseyngulu@mail.ru

Abstract- In order to normalize the voltage values in high-voltage buses of electric network and improve the mode reliability of power grid, the problem of synthesis of controller forming the control action on the basis of fuzzy sets and fuzzy logic for regulating the power of shunt reactors connected to compensate the charging power of the power line is considered. An algorithm for controlling the reactor power depending on the load resistance and its dynamics is proposed.

Keywords: Electric Network, Mode Reliability, Fuzzy Set and Fuzzy Logic, Charging Power.

I. INTRODUCTION

In extended high-voltage power lines (110-500 kV) and cable systems a shunt reactor (SR) is widely used to compensate for reactive power (charging power). Use of SR allows for solving such problems as unloading of power grid from the charging power in order to reduce losses, smooth and fast control of reactive power, damping of oscillations of active power and voltage on high-voltage buses, in general, the implementation of the tasks of improving the static and dynamic stability of the power system. SR can be directly connected to the power transmission lines, buses, three-phase transformer (autotransformer) permanently or by means of automatic switch [1, 2]. To improve the control of the required reactive power, reactor must have adjustable parameters.

If the load changes gradually (seasonally, daily or hourly), the use of controlled shunt reactor (CSR) may be one of the best problem solutions. At the same time, in the conditions of short-term and relatively long-term sharp fluctuations of the transmitted power and, accordingly, the load of the high-voltage power grid, the need for effective control of the SR, i.e. the optimal control of the required reactive power is created. In uncertain initial information conditions, the SR control management is subject to a number of difficulties. Under these conditions, the existing SR control systems cannot form a rational control action due to the problems of fluctuations and sharp deviations of voltage on high-voltage buses, as well as the occurrence of overvoltages associated with the implementation of frequent unreasonable switchovers [3, 4].

One of the options for the problem solving is the use of the transformer type SR produced by foreign (for example, ABB) firms with a thyristor control system, which has a core with an air gap filled with oil. As the studies show, when setting the controlled parameters in the conditions of real initial information data, the use of the SR with the control system implementing a particular traditional algorithm does not fully provide the desired results [5-7].

In this regard, under the above conditions, the creation of the algorithm and control system for SR on the basis of the theory of fuzzy sets and fuzzy logic proposed by the famous Professor L. Zadeh is topical and of scientific interest. The authors of this paper proposed such a system [6-8]. In this system the primary input parameters are the load resistance Z and its rate of change dZ/dt, and the controlled output parameter is the reactive power of the CSR. Despite the effectiveness of the CSR operation on the basis of the proposed fuzzy logic controller, the intellectualization of the facility is not fully provided, and in some cases there is a problem with the stabilization of the voltage on the high-voltage buses of the power grid. To eliminate these shortcomings, the task of improving and developing of the proposed control algorithm for the fuzzy logic controller (FLC) is assigned. For this purpose, the input and output vectors of linguistic variables are increased by one order, i.e. the current values of bus voltage were added to the input of the FLC, to which the CSR is connected, and to the output – the delay time of the control system action depending on the nature of the load resistance change (Figure 1).

Thus, the synthesized new type of FLC has a control system with three input and two output linguistic parameters, which allows for effective control of the output reactive powers of the CSR installed at the beginning and at the end of power transmission line of the power grid. In this paper, the synthesis and implementation of the FLC with three input and two output parameters for the CSR output power control in the initial fuzzy-probabilistic information environment are considered.

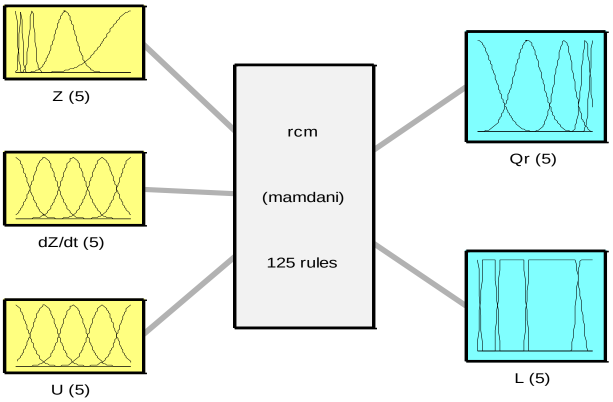


Figure 1. Fuzzy logic controller for CSR

II. CSR FUZZY CONTROL ALGORITHM

It is known that the "reactive power Q_r required by the CSR - line parameters" relationship is expressed by the formula [2, 3]:

$$Q_r = P_{nat} \cdot \lambda \cdot \left[1 - \left(\frac{P}{P_{nat}} \right)^2 \right] \cdot L \qquad (1)$$

where, P is active power transmitted over power PTL, P_{nat} is natural power of PTL, L is length of PTL and λ is wave length.

When controlling a reactor with a traditional control system, realizing the control algorithm worked-out based on the Equation (1), it is impossible to effectively regulate the reactive power of the CSR due to the above reasons. For this purpose, as it is shown in [8], the use of the theory of fuzzy sets and fuzzy logic of L. Zadeh is more justified. The proposed FLC for the CSR control has two inputs and one output and at fuzzy-probabilistic changes of the load resistance in the interval $Z = Z_d \div \infty$ (as the wave resistance of the line) implements the algorithm $\tilde{Q}_r = f\left(Z,\, dZ/dt\right)$.

As mentioned above, this control algorithm cannot fully provide a voltage stabilization on the buses. For this purpose, one more parameter was added for the input - the bus voltage, and for the output - the delay time of the FLC action, which is set depending on the load resistance change rate. The FLC implements two laws of fuzzy control:

$$\tilde{Q}_r = f\left(U, Z, \frac{dZ}{dt}\right) \quad , \quad t = f\left(U, Z, \frac{dZ}{dt}\right) \qquad (2)$$

It is known that any FLC consists of fuzzificator, fuzzy logic output mechanism and defuzzificator, and depending on the task, it implements the appropriate algorithm [3-7].

In this case, the fuzzy control algorithm (2) should be worked-out based on a fuzzy model of linguistic approximation with three input and two output parameters:

$$\text{if } X_1 = A_1 \text{ and } X_2 = A_2 \text{ and } X_3 = A_3 \text{ then } Y_1 = B_1 \text{ and } Y_2 = B_2 \qquad (3)$$

where, X_1, X_2, X_3 are input linguistic variables of the controlled objects; A_1, A_2, A_3 are fuzzy subsets defined in the universal sets E_1, E_2, E_3, respectively, consisting of terms of linguistic variables X_1, X_2, X_3; Y_1, Y_2 are output linguistic variables of the controlled objects; B_1, B_2 are fuzzy subsets defined in the universal sets E_4, E_5, respectively, consisting of terms Y_1, Y_2, where $\forall x_i \;\; A_i \in E_i ,\; i = 1...3$ and $\forall y_j \;\; B \in E_j ,\; j = 1,2$.

For input linguistic variables X_1, X_2, X_3, the membership functions of Gaussian (qaussmf), for output variables – *Z*-shaped (zmf), *S*-shaped (smf) and trapezoidal (trapmf) membership functions are adopted [6, 8]:

qaussmf function:

$$\mu_{ki}(x) = \exp\left(\frac{-(x_i - m_{ki})}{2\sigma_{ki}{}^2} \right), \quad i = \overline{1,n} \quad k = \overline{1,\, m} \qquad (4)$$

trapmf function:

$$\mu_{ki}(x) = \begin{cases} 0, & x_i \le a_{ki} \\ \dfrac{x_i - a_{ki}}{b_{ki} - a_{ki}}, & a_{ki} \le x_i \le b_{ki} \\ 1, & b_{ki} \le x_i \le c_{ki} \\ \dfrac{d_{ki} - x_i}{d_{ki} - c_{ki}}, & c_{ki} \le x_i \le d_{ki} \\ 0, & d_{ki} \le x_i \end{cases} \qquad (5)$$

zmf and smf functions:

$$\mu_{ki}(x) = \begin{cases} 1, & x_i \le a_{ki} \\ \text{nonlinear approximation}, & a_{ki} < x_i < b_{ki} \\ 0, & x_i \ge b_{ki} \end{cases} \qquad (6)$$

where, m is coordinate of the maximum; σ is concentration factor; a, d are fuzzy set carrier; b, c are fuzzy set kernel, and $\mu_{A,i}(x) : X_i \to [0,1]$.

After determining the fuzzy implication and the type of membership function on the basis of fuzzy approximation between the input and output vectors, the output signals are formed.

III. DETERMINATION OF PARAMETERS OF MEMBERSHIP FUNCTION AND DRAWING UP OF THE CONTROL ALGORITHM

Mamdani algorithm was used during drawing-up of FLC algorithm. During the programming on Mamdani algorithm ("reactor's reactive required power - line load" relationship), the following fuzzy subsets were accepted for input (load resistance and its rate of change) and output (reactor's reactive power) parameters:

- For "Load resistance" linguistic variable - term-subset $T_i(Z)$, where $Z_i \in E_{1i}$ c $i = \overline{1,5}$:

$$\begin{array}{lll} E_{11} = VB & \text{(very big)} & \underline{\underline{\Delta}}\left(Z, \mu_{11}(Z)\right) \\ E_{12} = B & \text{(big)} & \underline{\underline{\Delta}}\left(Z, \mu_{12}(Z)\right) \\ E_{13} = M & \text{(mean)} & \underline{\underline{\Delta}}\left(Z, \mu_{13}(Z)\right) \\ E_{14} = S & \text{(small)} & \underline{\underline{\Delta}}\left(Z, \mu_{14}(Z)\right) \\ E_{15} = N & \text{(natural)} & \underline{\underline{\Delta}}\left(Z, \mu_{15}(Z)\right) \end{array} \qquad (7)$$

For 500 kV PTL in real mode the wave resistance of 287 Ohms ($P_{nat} = 870$ MW) is accepted [1, 5, 6] , and the linguistic variable values Z of "Load resistance" are taken in the interval $Z = (287 \div \infty)$ Ohm. Generated random values of variable Z correspond to the power limit of $P = (870 \div 0)$ MW.

- The second input parameter of FLC is the "Dynamics" of fuzzy linguistic variable, where $T_j(dZ/dt)$ is term-subset, here $(dZ/dt)_j \in E_{2j}$ and $j = \overline{1,5}$.

$$\begin{array}{lll} E_{21} = VB & \text{(very big)} & \triangleq \left(dZ/dt, \mu_{21}\left(dZ/dt\right)\right) \\ E_{22} = B & \text{(big)} & \triangleq \left(dZ/dt, \mu_{22}\left(dZ/dt\right)\right) \\ E_{23} = ZR & \text{(zero)} & \triangleq \left(dZ/dt, \mu_{23}\left(dZ/dt\right)\right) \\ E_{24} = S & \text{(small)} & \triangleq \left(dZ/dt, \mu_{24}\left(dZ/dt\right)\right) \\ E_{25} = VS & \text{(very small)} & \triangleq \left(dZ/dt, \mu_{25}\left(dZ/dt\right)\right) \end{array} \quad (8)$$

$T_j\left(\frac{dZ}{dt}\right)$ term-set values are accepted within the $(-10 \div +10)$ interval.

- The third input parameter for the FLC is "Voltages" of fuzzy linguistic variable, where $T_k(U)$ is term-subset, here $(U)_k \in E_{3k}$ - and $k = \overline{1,5}$.

$$\begin{array}{lll} E_{31} = SB & \text{(very big - VB)} & \\ E_{32} = B & \text{(big - B)} & \triangleq \left(U, \mu_{32}(U)\right) \\ E_{33} = M & \text{(normal - M)} & \triangleq \left(U, \mu_{33}(U)\right) \\ E_{34} = S & \text{(small - S)} & \triangleq \left(U, \mu_{34}(U)\right) \\ E_{35} = N & \text{(very small - VS)} & \triangleq \left(U, \mu_{35}(U)\right) \end{array} \quad (9)$$

- The first output parameter of the FLC is "Reactive Power" for the fuzzy linguistic variable, $T_l(Q_r)$ is term-subset, $Q_{rl} \in E_{4l}$ and $l = \overline{1,5}$:

$$\begin{array}{lll} E_{41} = \max & \text{(maximum)} & \triangleq \left(Q_r, \mu_{41}(Q_r)\right) \\ E_{42} = B & \text{(big)} & \triangleq \left(Q_r, \mu_{42}(Q_r)\right) \\ E_{43} = M & \text{(mean)} & \triangleq \left(Q_r, \mu_{43}(Q_r)\right) \\ E_{44} = S & \text{(small)} & \triangleq \left(Q_r, \mu_{44}(Q_r)\right) \\ E_{45} = ZR & \text{(zero)} & \triangleq \left(Q_r, \mu_{45}(Q_r)\right) \end{array} \quad (10)$$

- The second output parameter of the FLC is "Delay time" for the fuzzy linguistic variable, $T_\gamma(t)$ is term-subset, $t_\gamma \in E_{5\gamma}$ and $\gamma = \overline{1,5}$:

$$\begin{array}{lll} E_{51} = VST & \text{(very short)} & \triangleq \left(t, \mu_{51}(t)\right) \\ E_{52} = ST & \text{(short)} & \triangleq \left(t, \mu_{52}(t)\right) \\ E_{53} = MT & \text{(mean)} & \triangleq \left(t, \mu_{53}(t)\right) \\ E_{54} = LT & \text{(long)} & \triangleq \left(t, \mu_{54}(t)\right) \\ E_{55} = VLT & \text{(very long)} & \triangleq \left(t, \mu_{55}(t)\right) \end{array} \quad (11)$$

The values of the linguistic variable "Reactive power" are accepted in the interval $P = (870 \div 0)$ MW.

In the Equations (7)-(11) the $\mu_{1i}(Z)$, $\mu_{2j}\left(dZ/dt\right)$, $\mu_{3k}(U)$, $\mu_{4l}\left(Q_p\right)$, $\mu_{5\gamma}(t)$ are the membership functions of term-sets of linguistic variables Z, dZ/dt, U, Q_p and t. These variables are respectively defined in the universal set $E_{1i}, E_{2j}, E_{3k}, E_{4l}, E_{5\gamma}$.

The FLC brings into action the reactor power control devices (Q_{r1}, Q_{r2}) depending on the input signals Z, dZ/dt, U and implement 125 fuzzy rules of type (3) based on the Mamdani algorithm.

The resulting fuzzy relationship R is determined as a union of fuzzy relations R_{ij} ($i, j = \overline{1,5}$):

$$R = \bigcup_{i,j,r,l,\gamma=\overline{1,5}} R_{ij} = \bigcup_{i,j,k,l,\gamma=\overline{1,5}} E_{1i} \times E_{2j} \times E_{3k} \times E_{4l} \times E_{5\gamma} \quad (12)$$

In this case the membership function of fuzzy relations is determined as follows:

$$\mu_R\left(Z, \frac{dZ}{dt}, U\right) = \max\left\{\min\left[\mu_{E_{11}}(Z), \mu_{E_{21}}\left(\frac{dZ}{dt}\right), \mu_{31}(U)\right],\right.$$
$$\min\left[\mu_{E_{12}}(Z), \mu_{E_{22}}\left(\frac{dZ}{dt}\right), \mu_{32}(U)\right], \quad (13)$$
$$\ldots,$$
$$\left.\min\left[\mu_{E_{15}}(Z), \mu_{E_{25}}\left(\frac{dZ}{dt}\right), \mu_{35}(U)\right]\right\}$$

where, max-min composition actions are used.

The definition area of input and output linguistic variables, values of parameters of the membership function of separate terms are given in Figure 2.

The control matrix-algorithm of reactor power in the format of fuzzy linguistic model "If-then" on the basis of linguistic models (5)-(9) is given in the Table 1. Fuzzy control matrix algorithm consists of 125 rules.

The antecedent part of each rule represents three, and the consequent part-two implications. For defuzzification, i.e. for transition from the phase of fuzzy control actions to a crisp control action, the centroid method [9] is used.

Table 1. SR fuzzy control algorithm-matrix

Options	Input parameters			Output parameters	
	Z	*dZ/dt*	*U*	*Q_r*	*L*
1	N	VS	VS	ZR	VLT
2	N	S	VS	ZR	MT
3	N	ZR	VS	ZR	ST
.	.	.	.	.	.
.	.	.	.	.	.
60	S	VB	S	S	LT
61	M	VS	S	ZR	ST
62	M	S	S	S	ST
.	.	.	.	.	.
.	.	.	.	.	.
123	VB	ZR	B	Max	VST
124	VB	B	B	Max	VST
125	VB	VB	B	Max	VST

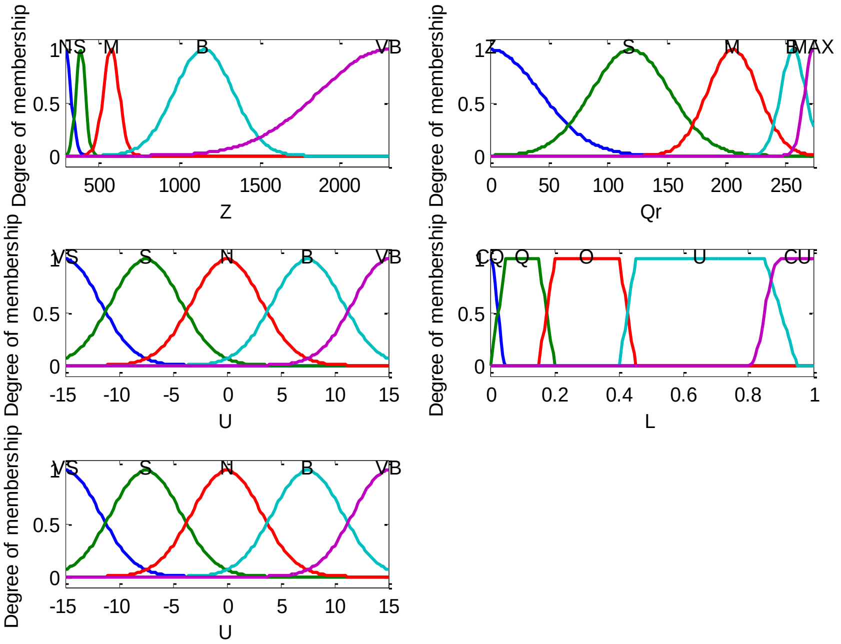
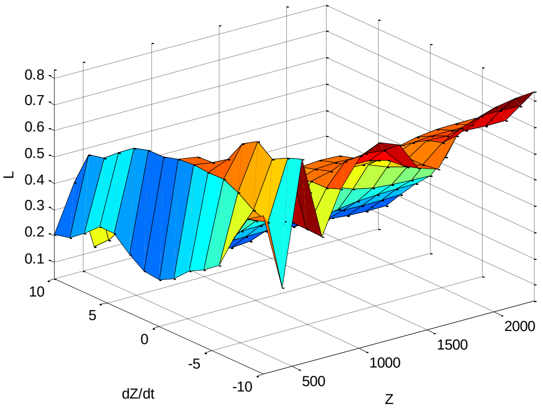


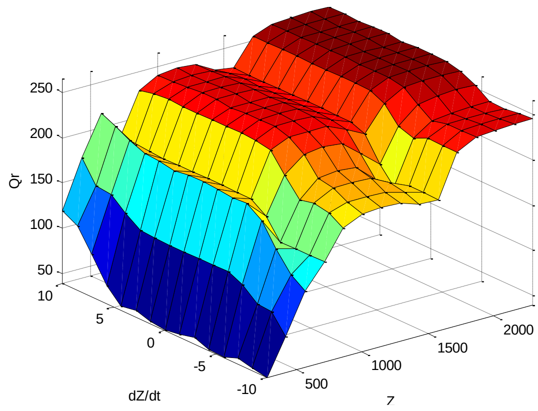
Figure 2. Membership functions of linguistic variable terms

IV. SIMULATION RESULTS

During the simulation the practical calculations are performed for operation of load of RODC-100/500 Y_1 type shunt reactors with the capacity of 280 MVA, that are actuated on both ends of the L=300 km long line with 500 kV voltage.



(a)



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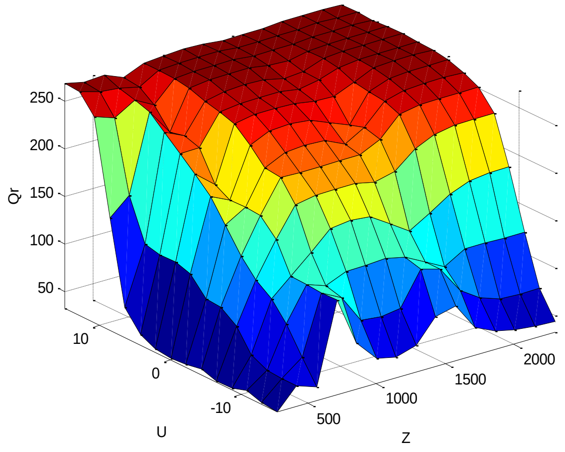
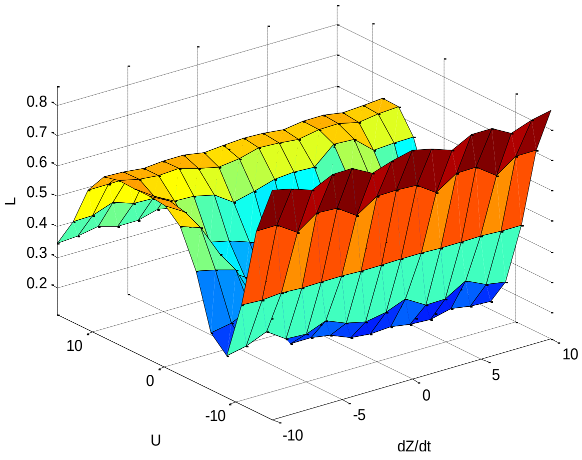


(c)



(d)

(a) $L=\tilde{f}\left(Z, dZ/dt\right)$, (b) $Q_r=\tilde{f}\left(Z, dZ/dt\right)$

(c) $Q_r=\tilde{f}\left(U, Z\right)$, (b) $L=\tilde{f}\left(U, \frac{dZ}{dt}\right)$

Figure 3. Control surfaces

The surfaces $Q_r = \tilde{f}\left(Z, \frac{dZ}{dt}\right)$, $L = \tilde{f}\left(Z, \frac{dZ}{dt}\right)$ obtained by means of the Fuzzy Logic Toolbox module in the Matlab environment, reflecting the dependence of the output parameters of the controller on the input ones, which show the action of the controller when controlling the power consumption of the SR are shown in Figure 3.

The SR fuzzy control algorithm has been tested for 500/330 kV intersystem power grid connecting power systems of Azerbaijan and Georgia.

On the basis of simulation modeling of the proposed fuzzy algorithm for SR control, the design experiments for different load modes of the electrical network are carried out. The obtained results for the voltage at the Samukh node of 500 kV Samukh-Gardabani PTL are shown on the Figure 4. As it is seen, at fuzzy SR control depending on overcurrents along the lines, the voltage on 500 kV buses is within the established standard.

The curves of the change of power losses during the control depending on the transmitted power in the line and the CSR power are shown on the Figure 5. As can be seen from the figures, at the fuzzy control of the reactive power flow, the active power losses in the considered network are reduced in the range from 0.26 to 0.178, i.e. to 31.5%.

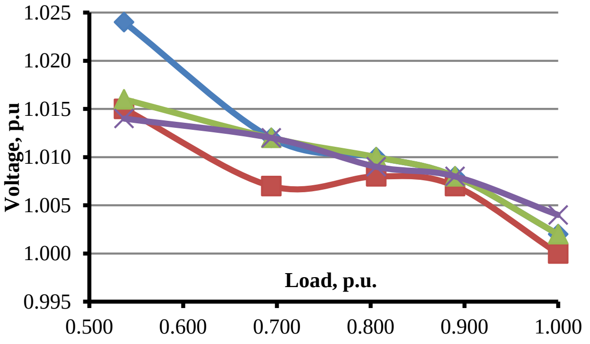


Figure 4. Curves of voltage change

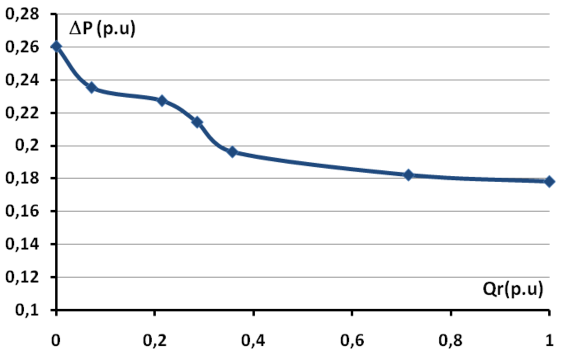


Figure 5. Change of power losses depending on 500 kV "Samukh-Gardabani" PTL CSR power

V. CONCLUSIONS

For the compensation of the voltage fluctuations on buses of high-voltage network of power grid, the fuzzy modeling algorithm is proposed to control the power of shunting reactors depending on the load resistance value, its rate of change and the bus voltage value.

The results of simulation modeling for the intersystem real electric network of power grids, which implements the proposed fuzzy control algorithm, confirm its effectiveness. At that, the voltages in the nodes of the high-voltage grid are within the specified permissible limits, and the power losses in the grid significantly decreased.

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BIOGRAPHIES

Arif Mamed Hashimov was born in Shahbuz, Nakhchivan, Azerbaijan on September 28, 1949. He is a Professor of Power Engineering (1993); Chief Editor of Scientific Journal of "Power Engineering Problems" from 2000; Director of Institute of Physics of Azerbaijan National Academy of Sciences (Baku, Azerbaijan) from 2002 up to 2009; Academician from 2007; the First Vice-

President of Azerbaijan National Academy of Sciences from 2007 up to 2013; and Director of Azerbaijan Research Institute of Energetics and Energy Design from 2014 till now. He is laureate of Azerbaijan State Prize (1978); Honored Scientist of Azerbaijan (2005); Cochairman of International Conferences on "Technical and Physical Problems of Power Engineering" (ICTPE) and Editor in Chief of International Journal on "Technical and Physical Problems of Engineering" (IJTPE). Now he is a High Consultant in "Azerenerji" JSC, Baku, Azerbaijan. His research areas are theory of non-linear electrical Networks with distributed parameters, neutral earthing and ferroresonant processes, alternative energy sources, high voltage physics and techniques, electrical physics. His publications are 310 articles and patents and 5 monographs.

Aytek R. Babayeva graduated from Power Engineering Faculty, Azerbaijan State Oil Academy, Baku, Azerbaijan in 2000. She defended the candidate of science (Ph.D.) dissertation on the theme of "Computer Modelling of Open-Phase Operating Condition of Electric Transmission Line and its Protection" in 2004. She is working in the Research Laboratory of High Voltage in Power Engineering and is the Scientific Secretary in Azerbaijan Research Institute of Energetics and Energy Design, Baku, Azerbaijan. Her scientific direction is monitoring the defense equipment from thunder with the aim to improve their efficiency and reliability.

Huseyngulu Bayram Guliyev received his M.Sc. and Ph.D. degrees and is a Lead Scientific Researcher, Manager of the Scientific Branch "Monitoring and Control of the Reactive Power" in Azerbaijan Research Institute of Energetics and Energy Design (Baku, Azerbaijan). Currently, he is an Associate Professor of Automation and Control Department in Azerbaijan Technical University (Baku, Azerbaijan). He has more than 140 published articles and 2 patents. His research interests are power systems operation and control, distributed generation systems, application of artificial intelligence to power systems control design and power quality.