International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2021 | Issue 47 | Volume 13 | Number 2 | Pages 76-81

RESEARCH OF OPTIMAL CONTROL OF SHUNT REACTORS ULTRA HIGH VOLTAGE POWER TRANSMISSION LINES

A.B. Balametov [1] E.D. Khalilov [1] T.M. Isayeva [2]

1. Azerbaijan Scientific-Research and Design-Prospecting Institute of Power Engineering, "Azerenerji" JSC, Baku, Azerbaijan, balametov.azniie@gmail.com, elmanxalilov2010@mail.ru
2. Azerbaijan State University of Oil and Industry, Baku, Azerbaijan, taranaisaeva@rambler.ru

Abstract- In this paper the problems of determining the optimal values of voltages and reactive powers of compensating devices for high-voltage (HV) overhead power lines are studied. The optimization of the ultra-high voltage power line mode is carried out in order to ensure minimum losses of the active power of the line on heating of the wires and the corona losses while maintaining the voltage within acceptable limits on maintaining voltage within acceptable limits. For optimal control of compensating devices of overhead ultrahigh-voltage transmission lines, an algorithm for the minimization of active power losses by reactive power of ultrahigh-voltage power transmission lines (UHV PTL), which is implemented using controlled shunt reactor (CSR) and STATCOM facilities, has been developed. For the optimal control of the compensating devices of the high-voltage power lines, an algorithm has been developed to minimize the loss of active power by the reactive power of the power lines of high-voltage lines using the CSR and STATCOM devices. Control of regulating and compensating devices based on local parameters is more reliably provided with initial information. The model proposed in the paper takes into account the corona power losses, which makes it possible to increase and increases the accuracy of modeling of modes of PTL. It is shown that the use of CSR in UHV PTL reduces the active power losses and increases the operating economy. On the example of 500 kV overhead line, appropriate recommendations are given for the control of CSR based on the measurement of the mode parameters at the ends of the transmission.

Keywords: Overhead Line, High Voltages, Reactive Power Compensation, Controlled Shunt Reactor, STATCOM, Active Power Losses, Corona Losses, Optimization, Optimal Voltage Drop.

1. INTRODUCTION

Voltage regulation of ultrahigh voltages (UHV) power lines (PL) is carried out in order to: maintain voltage within acceptable limits in the line and equipment under various operating conditions according to isolation conditions, exclusion of general corona, of unacceptable radio interference and acoustic noises; for restriction of charging power generated by the line to the system and generators in some modes; ensuring the stability of power transmission under heavy loads; ensuring a minimum of total losses of active power of the high voltage power lines and networks of lower voltage.

Based on this, the purpose of voltage regulation, in addition to ensuring a minimum of losses, is to reduce the total consumption in the electric network, especially for the modes of coincidence of the maximum load and maximum corona losses. Optimization of the modes of electric networks with high voltage power lines in terms of voltage and reactive power gives a significant economic effect.

Traditionally, the UHV PTLs are intended for the transmission of major powers from generation centers to electricity consumer zones. Usually, it is not a problem to control the voltage on the buses at the beginning of the UHV OHL by impacting on the excitation regulators of the generators of the power plant.

Maintaining of the voltage along the UHV PTL is carried out by regulating and compensating devices at terminal and intermediate HV substations.

Currently, in power systems, great importance is attached to the creation of controlled or flexible power transmission lines with FACTS devices [1]. For optimal control of the modes of such power systems, highly efficient reactive power control means are required.

Controlled shunt reactors have recently been widely used to control voltage and reactive power modes, in addition to generators, synchronous and static compensators, and switching reactors (Figure 1).

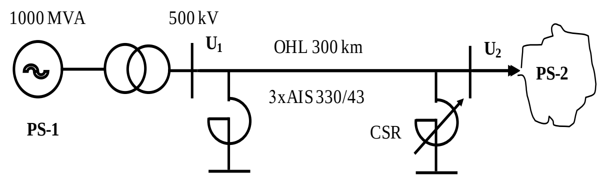

Figure 1. Scheme of part of the power transmission line with reactors

In the absence of SR, to normalize the voltage in different modes of active power transmission, effective operational measures are required, which can lead to large losses.

The creation of controlled shunt reactor, which allows for regulating line voltage with an accuracy of 1-2% [1-2], made it possible to effectively implement control systems of high voltage power lines. A more accurate change in the line voltage mode is possible with the combined use of regulating and compensating devices.

The control of regulating and compensating devices based on local parameters is more reliably provided with initial information and should be provided regardless of the availability of a control system of the upper level (automated supervisory control system).

Control based on local parameters has an independent meaning for cases of absence of a top level (SCADA), and also performs the functions of a backup control system in cases of receiving inaccurate information about control actions on the regulating and compensating devices of the substation and in the absence of this information for technical reasons.

The local control system, which uses only information on active power flows, corona losses in sections of OHL adjacent to this substation, and voltage control is carried out according to a simplified power transmission line model.

$$U_{\min} \le U_i \le U_{\max}$$

In [6], methods, algorithms and programs for optimizing the operating mode of UHV PTL by regulating reactive power at substations by reactive power sources were considered. The presence of longitudinal-transverse regulation transformers and shunt networks of lower voltage in the scheme of the UHV PTL network requires the coordination of their actions in order to obtain the optimal permissible mode.

The methods for control of compensating devices of a complex PS with UHV PTL and regulating RPS, transformers in the presence of shunt networks of lower voltage are considered below.

The voltage level at the transmitting end of the line can be set by generators as well as autotransformers with overvoltage regulators.

Currently, FACTS facilities, being one of the most perspective technologies for electric networks, form a comprehensive technical and information system for automatic control of power transmission line parameters [1-2]. First generation FACTS covers SCR controlled reactor, SCR series-controlled capacitor, phase shifting transformer, etc. Second generation FACTS includes facilities that provide regulation of the mode parameters based on fully controlled power electronics (IGBT-insulated gate bipolar transistors, IGCT- integrated gate-commutated thyristor, etc.). This type of FACTS carries out vector regulation, i.e. they regulate both the voltage vector phase and the vector module and have a new quality of regulation. Such facilities include a synchronous static compensator.

Increasing of the efficiency of the operation of individual overhead lines by regulating the voltage has been sufficiently studied and widely covered. A number of studies are devoted to determining the reasonable limits for regulating the voltage level of individual UHV power lines [3-6]. Optimization of the OHL voltage mode considering the corona power losses and wire heating was considered in [3-6].

The method [5] for voltage regulation in an individual UHV power transmission line, based on the comparison of increments of corona power losses and voltage heating of wires has been proposed:

$$\frac{d\Delta P}{dU} = \frac{d\Delta P_{н}}{dU} + \frac{d\Delta P_{к}}{dU} = 0$$

$$l_{*э} = \frac{1}{L} \cdot \int_0^L \left(\frac{U_x}{U_2} \right)^{\rho} dx = \psi \ \{R_0,\ P_2,\ \Delta P_{к},\ L\}$$

A criterion method has been developed for identifying the optimal proportionality of corona losses and losses for heating wires to determine the of voltage control law of OHL. The optimal proportion of losses for corona and heating of wires, expressed as fractions of the total losses for a certain 500 kV OHL, considered in [6] for good weather and dry snow is 19-20% for corona losses, 80-81% for the heating of wires and during the rain 32-35% and 67-68%. This expression can be used to determine the direction of change in the voltage of the power transmission line, which reduces the total losses.

The greatest effect from optimal control can be obtained with SCADA EMS by means of integrated control of regulating and compensating devices of the entire power system.

2. OPTIMAL VOLTAGE OF ULTRAHIGH VOLTAGE OVERHEAD POWER LINES WITH CONCENTRATED PARAMETERS ACCORDING TO THE π-MODEL

For the more accurate simulation of the operating mode, the transmission line is presented in the form of elements connected in circuit. The equivalent scheme consists of π-model sections connected in circuit as Figure 1 [7-8].

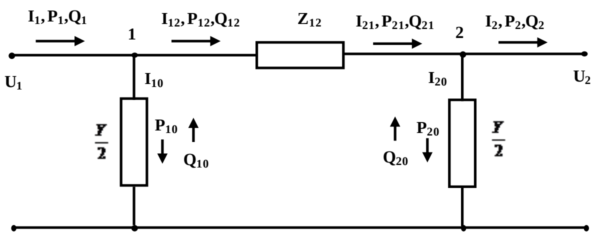

Figure 2. Calculation scheme of the line section

Optimization of the mode of UHV PTL according to U_1 and Q_2. The objective function in optimizing the mode of UHV OHL in the form of the sum of power losses for heating of wires $\Delta P_н$ and for the corona $\Delta P_к$.

$$\Delta P_{сум} = \Delta P_н + \Delta P_к \quad (1)$$

Limitations on the highest voltages of electrical equipment of substations

$$U_{i\min} \le U_i \le U_{i\max} \quad (2)$$

where, $U_{i\min}$ and $U_{i\max}$ are the smallest and largest allowable voltages of the transmission line and equipment.

For the losses for heating of wires we have

$$\Delta P_{н} = \frac{\left(P_2 + 0.5G_k U_2^2 + G_r U_2^2\right)^2 + \left(-Q_2 - Qr + 0.5B_c U_2^2\right)^2}{U_2^2} R$$

For the losses for corona of wires we have

$$\Delta P_{к} = G_r U_2^2 + 0.5G_k \left(U_1^2 + U_2^2\right)$$

$$I_{21}^2 = \frac{P_{21}^2 + Q_{21}^2}{U_2^2},\ \Delta P_{н} = I_{21}^2 R$$

where, P_2, Q_2, U_2 are, respectively, the active, reactive powers and voltage of the end of the π-shaped line equivalent circuit, R is the actual active resistance of OHL wires. Voltages limitations at the beginning and end of power lines.

$$U_{\min} \le U_i \le U_{\max}$$

3. OPTIMAL VOLTAGE OF UHV OHL

Equating to zero the partial derivative of the total voltage losses of the overhead line, after the transformations we obtain the expression for the optimal voltage of the end of the line

$$U_2 = U_{н} \sqrt[(\rho+2)]{\frac{4[(P_2^2 - g^2U^4) + Q'^2]R}{\rho(1+k_U^{\rho})\Delta P_k U_{н}}} \quad (3)$$

where, U_n is the rated voltage of the OHL, P_2 is the active power at the end of the OHL, ΔP_{k0} is the specific corona power losses, R is the active resistance, $\Delta P_k = L\Delta P_{k0}$ and L is the length of the OHL

Obtaining explicit expressions for the optimal voltage and reactive power when considering losses on the corona as a voltage function of 4-8th degree is not possible. Therefore, a more accurate algorithm for minimizing the active power losses of UHV OHL is reduced to iterative refinement.

For practical calculations, the formula for the optimal voltage of the UHV OHL can be determined by calculating the mode of line at a given voltage at the beginning and end of the line ($U_1 = U_2 = U_n$) and at active power flow. At the optimum point of the total losses in the UHV OHL, the corona losses are amounted to 0.5ρ of losses for heating of the wires.

It should be noted that the value ρ = 4 usually corresponds to the characteristic of losses for bad weather [3, 6]. The value ρ = 6 corresponds to the average annual losses, and at the same time, at the optimum point, the corona losses are 1/3 of the losses for the heating of the wires. The value ρ = 8 corresponds to good weather, and at that, at the optimum point the corona losses are 1/4 of the losses for the heating of the wires.

Determining of the optimal U and Q from the equations of the line with distributed parameters and taking into account the corona in the form of a voltage characteristic of ρth degree requires a relatively complex optimization algorithm using non-linear programming methods.

The optimal change of voltage of the UHV PTL depends on the phase design, the length of the line, the transmitted active power and the level of corona losses. In general, the dependence for the optimal change of voltage can be represented as

$$l_{*э} = \frac{1}{L} \cdot \int_0^L \left(\frac{U_x}{U_2}\right)^{\rho} dx = \psi\ \{R_0,\ P_2,\ \Delta P_{к},\ L\} \quad (4)$$

The expressions for the "value of ρth degree voltage integral along the line - geometric length of the line" relationship, which characterizes the relative change in corona power losses taken into account the voltage distribution along the line, can be represented as

$$K_U = \varphi\{R_0,\ P_2,\ \Delta P_{к},\ L\} \quad (5)$$

where, R_0 is the active resistance per unit length of the line, and U_2 is the voltage on the end of the line. When calculating power losses in OHL, the active resistance R_0 is usually assumed constant. In real conditions the resistance of a wire depends on its temperature. In particular, the temperature of wires of PTL is determined by the heating of the current flowing through them and the cooling conditions in the environment. Therefore, in the optimization calculations of PTL modes, it is necessary to consider the updated values of active resistance of the line taking into account the temperature.

The expressions for the optimal change of voltage of the UHV PTL are determined by approximation of the results obtained according to the full optimization model of the UHV PTL [6] by a polynomial of the 2nd degree depending on the transmitted active power, line length, level of specific corona power losses and active resistance per unit length of the line.

The value of K_{uopt} increases with the growth of PTL length, transmitted power, level of specific corona losses and decreases with the decrease of active resistance per unit length (with the growth of equivalent radius of wire) of the line.

The value of $l_{*э}$ increases with the growth of line length and decreases with the growth of transmitted active power of the line, the value of specific corona losses and total active resistance per unit length of the line.

Dependence (4-5) for the optimal changes of voltage is obtained from the condition of achieving minimum active power losses without considering the limitation on voltage in the line. The following limitations must be considered for UHV PTL: for the long-term permissible voltage of OHL U_{dvl} from the conditions for exclusion of total corona effect and unacceptable radio interferences.

In this paper, in order to obtain the dependences K_{uopt} and $l_{*э}$, a technique is considered based on modeling of the PTL modes according to the full optimization model of the mode for voltage and reactive power and approximation of the obtained dependences for K_{uonm} and $l_{*э}$. Calculations were performed according to the method [3] for the determining of the optimal change of voltage for 500 kV PTL with the parameters given in Table 1, at PTL lengths of 300 km, at values of the transmitted active power of 0.5, 0.75, 1 and 1.1, respectively, of the power of 900 MW.

The optimal changes of voltage of 500 kV PTL with 3×AC-330/43 conductors, obtained according to the full optimization model, are presented in Table 1 [6].

The value of K_{uopt} increases with an increase in the PTL length, the transmitted power, the level of specific corona losses and decreases with a decrease in the active resistance per unit length (with an increase in the equivalent radius of the conductor) of the line.

Table 1. The dependences of optimal change of voltage for 500 kV PTL

P_2 MW	L km	At values of specific corona losses $\Delta P_{к0}$ W/m				
		2.5	10	25	50	100
For 500 kV OHL with 3×AC-330/43 conductors						
450	300	1.0133	1.0174	1.0210	1.0257	1.0325
675		1.0168	1.0221	1.0257	1.0297	1.0372
900		1.0200	1.0262	1.0297	1.0324	1.0410
990		1.0211	1.0277	1.0311	1.0335	1.0424

The change of voltage of the PTL site under non-optimal modes, depending on the mode of active power transmission and at maintaining of technically permissible voltages, K_{uopt} = 1.1 or more can take place, i.e. more than 10% of the nominal line voltage.

The optimal values of the change of voltage for UHV PTL, depending on P_2, $\Delta P_{к0}$, L, R_0 place within 1.01-1.03, i.e. less than 3% compared to the results of the full optimization model. The maximum approximation error for the K_{uopt} dependence is less than 0.3% or about 10% of the voltage drop.

The dependence for optimal changes of voltage was obtained from the condition of achieving minimum active power losses without taking into account the line voltage limitations.

Optimal voltages of 1150 kV overhead lines with a phase design of 8×AC-300 and a length of 500 km are analyzed depending on the transmitted power for various values of specific corona power losses. The calculation results obtained from the condition of achieving minimum active power losses without taking into account the line voltage limitations are presented in Figure 3.

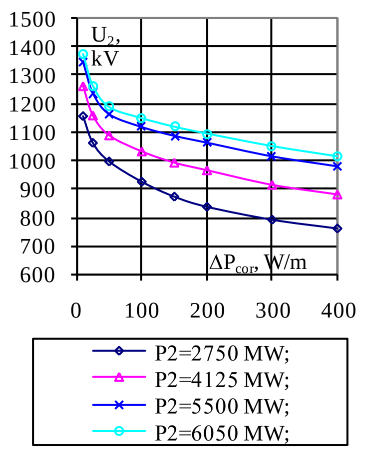

Figure 3. The dependences of the optimal voltage of 1150 kV OHL with a length of 500 km, corresponding to the mode of minimum losses

At the same time, with an increase in the level of the transmitted active power, the values of the optimal voltages increase. With the increase of the values of the specific corona losses, the values of the optimal voltages decrease.

To analyze the optimal change of the voltage at the end, the calculations were performed according to the full optimization model of 1150 kV OHL with a line length of 500 km and at different levels of specific corona losses, an exponent of the corona characteristic and for various values of active power transmitted through the overhead line (Figure 4).

The optimal change of voltage of corona 1150 kV OHL with a length of 500 km is 0.5-3.5% higher than the optimal voltage at the end of the line, i.e. the mode with the change of voltage equal to 1.005-1.035 corresponds to the optimal mode of OHL. At that, the change of voltage increases with the growth of the transmitted active power, specific corona power losses and line length.

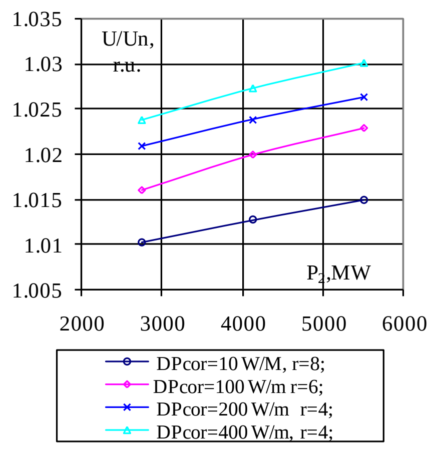

Figure 4. The voltage change curves of the 1150 kV OHL, corresponding to the mode of minimum losses of the transmitted power at l = 500 km

A complete algorithm for optimizing the mode of UHV PTL according to line equations in hyperbolic functions, taking into account the characteristics of the corona power losses from the voltage and voltage distribution along the line, is relatively complex, time-consuming and requires a significant time consumption of computer even for one section of the UHV PTL.

When choosing voltage control algorithms for UHV PTL, it is necessary to take into account the information richness of the optimization problem. A control system based on local parameters can be used both independently and as a backup control system. Therefore, the problem of control of regulating and compensating devices based on local parameters is of great importance for optimal control of UHV PTL.

Optimization of the modes of electric networks with UHV PTL in terms of voltage and reactive power gives a significant economic effect and has the following features: the optimal voltage level of UHV PTL depends on weather conditions that determine the level of power losses for corona effect of OHL; as part of the electrical network, they perform a system-forming function, and usually have lower voltage shunt networks; the operation modes of electric networks with UHV OHL have a wide variety, determined by the daily and seasonal nature of the load changes, the changing of the direction of the power flow of OHL, the large charging capacities.

The corona power losses of the UHV PTL under bad weather conditions, is commensurate with the unit capacity of the generator of the power plant, and to cover it additional capacities are required. Based on this, the purpose of voltage regulation, in addition to ensuring a minimum of losses, is to reduce the total consumption in the PS, especially for the modes of coincidence of the maximum load and maximum corona losses.

Control based on local parameters has an independent significance for cases of lack of the upper level of ASCS, and also acts as a backup control system in cases of receiving inaccurate information about the control actions on the regulating and compensating devices (CD) of the substation and the line in the absence of this information for technical reasons.

In general, one can consider the following voltage control systems for the UHV power transmission: centralized, decentralized and local control system that uses only information on active power flows or corona losses.

4. SIMULATION

Wire grade 3×AC-330/43, slitting step of 0.4 m, R_0 = 0.029 Ohm/km, x_0 = 0.299 Ohm/km, b_0 = 3.74 10^{-6} cm/km, specific corona losses corresponding to good weather are accepted ΔP_{k0} = 4 W/m, an indicator of the degree of dependence of voltage corona losses is adopted as ρ = 5. The length of the OHL is 300 km.

The dependences of the optimal change of voltage for 500 kV PTL with 3×AC-330/43 wires from active power and specific corona losses, U_2 = 500, with specific corona losses ΔP_{k0}= 4 W/m, voltage index ρ = 5 are presented in Table 1.

Table 1. Results of calculation for 500 kV modes

P_2, MW	Q_2, MVAr	U_1, kV	ΔP_{sum}, MW	ΔP_n, MW	ΔP_k, MW	U_1/U_2, p.u.
900	55	524.984	29.15	27.799	1.363	1.0499
700	120	522.909	18.149	16.778	1.3708	1.045
500	125	513.225	10.0038	8.683	1.32	1.026
300	100	500.638	4.583	3.333	1.249	1.0012

The dependence of the optimal change of voltage of 500 kV OHL from active power is shown in Figures 5 and 6.

The calculation results show that the optimal voltage at the beginning of the line, depending on the length of the line, the value of the transmitted power, specific corona losses is 0-5% higher than the nominal voltage of the end of the line, i.e. the optimal mode of OHL with a length of 300 km corresponds to a mode with the change of voltage of 1-1.05. At that, the change of voltage increases with the growth of transmitted active power, specific corona power losses and line length.

Usually, the equivalent characteristics of the receiving EPS are not known. To do this, it is necessary to consider the full scheme of the EPS with the UHV PTL under consideration. They can be obtained from experimental data during the control process according to measurements based on flows in sections adjacent to the node.

The CSR can be set to the position corresponding to the optimal mode of the UHV PTL for the minimum of the active power losses. For example, by automatic control of CSR, to achieve maintaining of the voltage in the node close to 500 kV.

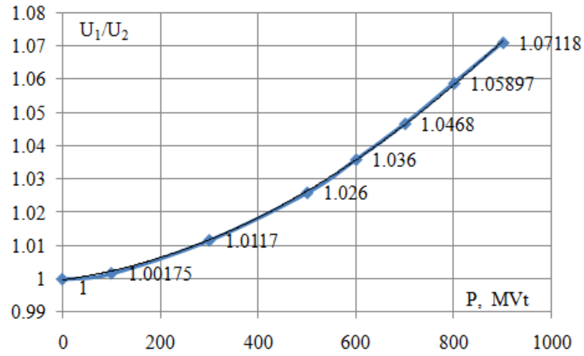

Figure 5. Change of the optimal voltage drop of OHL 500 kV on the active power without taking into account restrictions

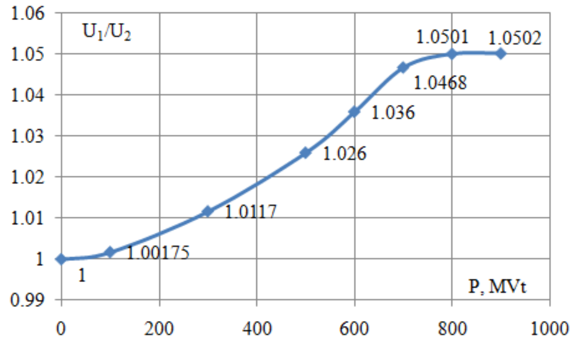

Figure 6. The dependence of the optimal voltage drop of 500 kV OHL from the active power, considering the limitations

The dependence of the optimal voltage of 500 kV OHL from reactive power is shown in Figure 7.

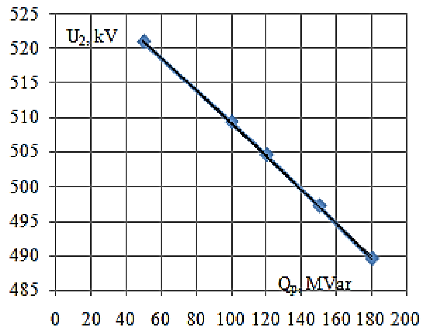

Figure 7. Change of the optimal voltage of the overhead line on dependence of the reactive power of the CSR

Figure 8 shows the curves of the "active power losses of 500 kV OHL - reactive power" relationship are presented in Figure 8.

According to the results of the experiment, it is possible to construct an equivalent characteristic of the receiving EPS. For example, let us set the equivalent characteristic of the dependence of the reactive power of the receiving EPS in the form of $Q_{ekv.ch.EPS} = b_0 + b_1 U_2$.

For the reactor, one can set Q, CSR control. When specifying CSR with conductivity, the corresponding conductivity can be calculated as $Q_p = G_p U_2^2$.

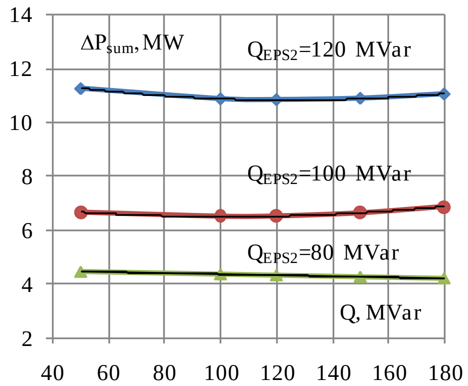

Figure 8. Dependences of active power losses on the value of reactive power of SR

5. CONCLUSIONS

1. The optimal values of the voltage and reactive power of the UHV OHL, depending on the value of the transmitted power, the weather conditions of the OHL route vary within 1.005-1.05. The value of the optimal change of voltage increases with the growth of the PTL length, transmitted power, level of specific corona losses.

2. A complete model is proposed for the numerical simulation and optimization of the mode of radial UHV PTLwith intermediate substations, in terms of voltage and reactive power, taking into account the corona power losses, which makes it possible to increase the accuracy of simulation of modes of PTL.

3. The use of CSR in UHV PTL along with known positive effects allows for reducing the active power losses and increases the efficiency of operation.

REFERENCES

[1] G.N. Alexandrov, "The methodology for calculating controlled transformer-type shunt reactors", Electricity, No. 6, 1994.
[2] V.I. Kochkin, "Guided shunt reactors for high voltage power lines", Power Engineering, No. 5, 1999.
[3] A.B. Balametov, "Regularities of the optimal regulation of voltage and reactive power of UHV OHL" Electricity, No. 9, 1998.
[4] A.I. Tamazov, "Crown on wires of OHLs". M.: Sputnik, 2002.
[5] Yu.N. Astakhov, V.V. Moskalenko, "The law of voltage regulation controlled by power lines", Sat scientific works: Management of Power Transmission Modes. Chisinau: Shtiintsa, 1988.
[6] A.B. Balametov, "Coroning of wires of UHV OHL - Modeling in steady state", Monograph, LAP Lambert Academic Publishing, p. 310, 2013.

BIOGRAPHIES

Ashraf B. Balametov was born in Qusar, Azerbaijan, on January 27, 1947. He received the M.Sc. degree in the field of Power Plants of Electrical Engineering in the Azerbaijan Institute of Oil and Chemistry, Baku, Azerbaijan in 1971, the Candidate of Technical Sciences (Ph.D.) degree in the Energy Institute named after G.M. Krzhizhanovskiy, Moscow, Russia and Doctor of Technical Sciences degree in the Novosibirsk Technical University, Russia in 1994. He is a Professor in Azerbaijan Research and Design-Prospecting Institute of Power Engineering, Baku, Azerbaijan. His research interests are steady state regimes, optimization and power system control.

Elman D. Khalilov was born in Baku, Azerbaijan, on March 23, 1962. He received the M.Sc. degree in the Baku State University, Baku, Azerbaijan and the Ph.D. degree in the Azerbaijan Research and Design-Prospecting Institute of Power Engineering, Baku, Azerbaijan in 2000. His research interests are steady state regimes, optimization and power system control.

Tarana M. Isayeva was born in Shirvan, Azerbaijan on May 24, 1969. She received the M.S. degree in Electrical Engineering in the Azerbaijan State Oil Academy in 1991 and the Candidate of Technical Sciences (Ph.D.) degree in Azerbaijan Research and Design-Prospecting Institute of Power Engineering in 2007. She is Asst. Prof. in the Azerbaijan State Oil and Industry University, Baku, Azerbaijan. Her research interests are power quality and power management.