METHODS INDEMNIFICATION OF REACTIVE CAPACITY IN THE ELECTRIC NETWORK FOR INCREASE OF REGIME RELIABILITY OF THE POWER SUPPLY SYSTEM

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ABSRACT

There are considered questions of a choice and placing of devices of the battery of static condensers in distributive electric networks of power supply systems for indemnification of reactive capacity, on the basis of technical and economic indicators and investment possibilities of a power supply system. Given results of settlement experiments of realization of an offered methods for the typical distributive network, characterizing technical and economic efficiency of the made decision are resulted.

Keywords: power supply systems, a distributive electric network, batteries of static condensers, indemnification of reactive capacity.

I. INTRODUCTION

Problems of rise of efficiency and regime reliability of electric power systems at the expense of decrease of losses of the electric power in electrical networks by means of a reactive power compensation (RPC) is the important provision on an energy conservation. Thus the all-round energy conservation can be observed as alternative in relation to the large-scale escalating of power powers on large power stations.

Methodically the problem of sampling and disposing of devices RPC dares as follows. The supply authority should install meaning of a reactive power which should be transmitted from an electric power system in a consumer web (an economic reactive power – $Q_{эк}$), and a deficiency of a reactive power of consumer webs should become covered at the expense of its generation in webs at the expense of batteries of statistical capacitors (BSC) [1-4] or other modes, for example, by application of a thrystors radiant of a reactive power [5].

In the conditions of market economy electrical networks of electric power systems belong to various departments and consequently solving problems BSC it is represented as a complex technical and economic problem. Thus determination $Q_{эк}$ should dare on the basis of technical-and-economic indexes and investment possibilities of an electric power system, and consumer webs are obliged to realize local BSC ensuring set $Q_{эк}\,(tg\varphi_{эк})$, or to them sanctions in the form of the allowance to the tariff for use by electric energy should be applied.

Practically the technique of sampling and disposing of operated compensating devices (CD) in electrical networks of electric power systems consists in definition of summarized power CD, and then their optimum disposing, with determination of sequence of their installation, in electric power system knots.

The sampling and disposing problem operated BSC in distributive electrical networks of electric power systems is in-process observed.

II. CRITERION FUNCTIONS AND ACCEPTED RESTRICTION AT CRC

On the basis of experience of the solution of the given problem and the developed economic mutual relations at the optimum complex solution of problem CRC the optimization equations in a following aspect [6] are used:

1. Criterion function

$$F = \sum \Delta\Delta W_{ann} = \Sigma\left(\Delta W_{ann}^{b.c} - \Delta W_{ann}^{a.c}\right) \rightarrow \max,$$

$$\Sigma E_{ann} = \left(\sum \Delta\Delta W_{ann} \cdot \beta - \frac{\sum C_{CD}}{n_c}\right) \rightarrow \max$$

$$T_{pb} = \frac{\sum C_{CD}}{\sum \Delta\Delta W_{ann} \cdot \beta} \rightarrow min$$

where: $\Delta\Delta W_{ann}$ - annual economy of the electric power owing to compensation;

$\Delta W_{ann}^{b.c}$, $\Delta W_{ann}^{a.c}$ - annual losses of energy before and after compensation;

β – the cost price of manufacture of the electric power in power supply system;

$\sum C_{CD}$ - total expenses for CD installation;

n_c - serviceability of the capacitor battery.

2. The restriction equations:

$$\sum Q_c^{add} \le \left(P_{c,\max} \cdot a - Q_{k,exs}\right)$$

$Q_{ci} \le Q_{H,i,min}$ – non - adjustable CD

$Q_{ci} \le Q_{H,i,max}$ – adjustable CD

$$\sum C_{CD} = C_c \sum Q_c^{add} \le C_{inv.}$$

$$U_{\kappa \min} < U_k < U_{k \max}$$

where

$\sum Q_c^{add}$ - in addition necessary CD power;

$P_{c,max}$ - the maximal power supply system;

a - the equipment factor of the CD power supply system $(a \approx 0{,}2)$;

$Q_{c,exs}$ – capacity of existing CD;

$Q_{ci,}$ $Q_{H,i,min,,}$ $Q_{H,i,max}$ - necessary CD power, minimal and maximal reactive power in *i* node;

C_c - specific cost of CD$\left(\frac{\$}{MBAp}\right)$;

C_{inv} - amount of the allocated investment on CD installation in a power supply system (in region);

$U_{\kappa \min}, U_{k \max}$ - the minimal and maximal values of the voltage in *k* node.

3. Constraint equation.

The program of calculation of the established mode of the electric network (CEMEN) - for definition $\sum \Delta W = \sum \Delta P \cdot \tau$

$m_i = \frac{\partial \sum \Delta\Delta W}{\partial Q_c}$ - for definition of the sequence of CD installation

where $\Delta P, \tau$ - ctive power losses in a mode of the maximal loading, number of hours of use of the maximal losses *(τ= 4000-5000 hours).*

m_i - sensitivity of alteration of losses at changing of the CD power in *i* node.

Economic benefit from CRP is achieved owing to:

- reduction of energy losses in air and cable lines and in transformers.

$$\Delta\Delta W = \Delta\Delta P \cdot \tau \; ; \quad C_{\Delta P} = \Delta\Delta W \cdot \beta$$

- increase in throughput of lines and transformers, which is taken into account by corresponding shares of their cost, i.e.:

for lines with admissible current $\dot{I}_d$

$$\Delta K_l = K_l (I_1^2 - I_2^2) / I_d$$

for transformers

$$\Delta K_T = K_T (S_1 - S_2) / S_1$$

Here K_l and K_T - cost of lines and transformers.

Annual economic benefit

$$E_{ann} = C_{\Delta P} - C_{CD} / n$$

Pay-back period

$$T_{pb} = (C_{CD} - \Delta K_T - \Delta K_l) / C_{\Delta P}$$

III. METHOD OF SAMPLING CD IN DISTRIBUTIVE ELECTRICAL NETWORKS OF ELECTRIC POWER SYSTEMS

The principle of sampling CD in distributive electrical networks is based on security of an economic reactive power - $Q_{эк}$ or $tg\varphi_{эк}$. Thus CD, ensuring $Q_{эк}$ in a point of association of a distribution net (DN) to an electric power system, it can be installed in various points [7-9].

At installation CD on buses of a high voltage of the feed source, i.e. in a point 4 power CD will be

$$Q_{к4} = Q_4 - Q_{ek} = Q_4 - P_4 \cdot tg\varphi \tag{1}$$

At installation CD on a low leg of substation on supply net buses, in a point 3 $Q_{к3}$ it is had:

$$Q_4^{ac} = Q_3 - Q_{k3} + \Delta Q_{T1}^{ac} = Q_{ek} = P_4^{ac} \cdot tg\varphi$$

Where $P_4^{ac}, Q_4^{ac}, \Delta Q_{T1}^{ac}$ – active and reactive powers on buses 4 and reactive power losses in transformer T1 after compensation.

Here

$$\begin{aligned} Q_{k3} &= Q_4 - Q_{4ek} = Q_3 + \Delta Q_{T1} - P_4^{\;ac} \cdot tg\varphi = Q_3 + \Delta Q_{T1}^{\;\;ac} - (P_3 + \Delta P_{T1}^{\;\;ac})tg\varphi = \\ &= Q_3 - P_3 tg\varphi + \frac{P_3^2 + (Q_3 - Q_{k3})^2}{U_3^2} x_{T1} - \frac{P_3^2 + (Q_3 - Q_{k3})^2}{U_3^2} r_{T1} tg\varphi = \\ &= Q_3 - P_3 tg\varphi + \frac{P_3^2 + Q_3^{\;2}}{U_3^2} x_{T1} - \frac{P_3^2 + Q_3^{\;2}}{U_3^2} r_{T1} tg\varphi - 2Q_3 Q_{k3} \left(\frac{x_{T1} - r_{T1} tg\varphi}{U_3^2}\right) + \\ &+ Q_{k3}^2 \left(\frac{x_{T1} - r_{T1} tg\varphi}{U_3^2}\right) = Q_{k4} - [2Q_3 Q_{k3} - Q_{k3}^2] \frac{x_{T1} - r_{T1} tg\varphi}{U_3^2} \end{aligned} \qquad (2)$$

In expression (2) $2Q_3Q_{k3} - Q_{k3}^{\;\;2} > 0$, since $Q_3 > Q_{k3}$, hence, $Q_{k3} < Q_{k4}$.

Meaning of power CD Q_{k3} we will discover from the following quadratic equation gained after transformation (2)

$$\frac{x_{T1} - r_{T1} tg\varphi}{U_3^2} Q_{k3}^2 - \frac{x_{T1} - r_{T1} tg\varphi}{U_3^2} 2Q_3 Q_{k3} - Q_{k3} + (P_3^2 + Q_3^2) \frac{x_{T1} + r_{T1} tg\varphi}{U_3^2} + Q_3 - P_3 tg\varphi = 0 \qquad (3)$$

In observed case Q_{k3} it is defined according to $U_3, P_3, Q_3, tg\varphi, r_{T1}, x_{T1}$.

From two roots of an equation (3) it is accepted $0 > Q_{k3} < Q_3$ which will ensure demanded tgφ on a substation high-tension side.

At desire of definition Q_{k3} it is direct according to P_4, Q_4 in the formula (3) meanings P_3, Q_3 are substituted from expressions:

$$\mathrm{P}_3 = P_4^{bc} - \frac{(P_4^{bc})^2 + (Q_4^{bc})^2}{U_4^2} r_{T1}$$

$$\mathrm{Q}_3 = Q_4^{\mathrm{bc}} - \frac{(P_4^{\mathrm{bc}})^2 + (Q_4^{bc})^2}{U_4^2} x_{T1}$$

Where, P_4^{bc} Q_4^{bc} - meaning active and a reactive power before compensation.

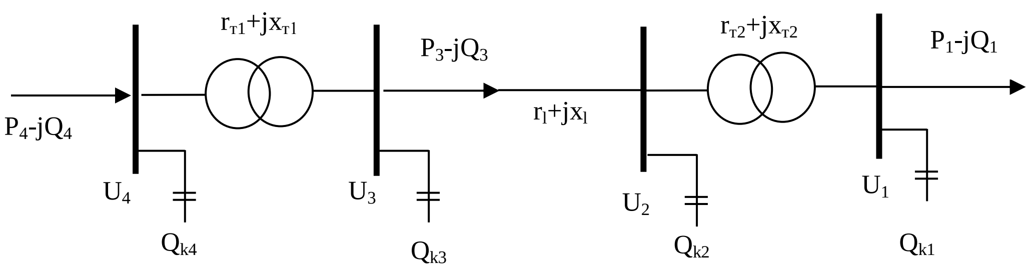

Fig. 1. The typical circuit design of a supply net

Let's accept:

$$A = \frac{x_{T1} - r_{T1} tg\varphi}{U_3^2}$$

$$B = (\frac{x_{T1} - r_{T1} tg\varphi}{U_3^2} \cdot 2Q_3 - 1)$$

$$C = (P_3^2 + Q_3^2)\,\frac{x_{T1} + r_{T1} tg\varphi}{U_3^2} + Q_3 - P_3 tg\varphi$$

Then

$$AQ_{k3}^2 - BQ_{k3} + C = 0$$

Apparently from (3) meaning of reactive power CD it is defined affiliated active both a reactive power of a knot and active and jet by resistance between a point of association of a supply net to an electric power system. Therefore at installation CD in a knot 2 to resistance r_{T1} and x_{T1} it is necessary to add r_l and x_l lines 2-3, and at installation CD in a knot 1 still r_{T2} and x_{T2}, voltage led to one step, for example to voltage U_4.

In case the supply net is represented several departing from buses 3 (10 kV) lines it is expedient to define at first the general power which is necessary for installing in this supply net, and then it to distribute between knots of loadings to proportionally their reactive powers.

IV. RECOMMENDATIONS ABOUT DISPOSING BSC IN ELECTRIC POWER SYSTEM NETS

In existing webs for definition of a place of disposing new CD it is necessary to have the information on reactive loadings on substation. The most authentic data are the winter and summer indications spent in an electric power system. On the basis of the indications spent in real electric power system in winter phase, the analysis of a relationship jet and an active-power ($tg\varphi$) on all central substations *110 kV* is made φand knots with the greatest meanings of these relationships are revealed. For 7 substations where $tg\varphi > 0{,}4$ powers CD are defined, adoption in limits (0,2-0,3) $P_{\max}$ and their effectiveness's are defined, at various meanings τ, C_{CD} resulted in table 1. In association about volume of investments summarized power CD, and on it annual economic benefit E_a and pay-back period the Current is chosen.

For reaching of the greatest efficiency it is necessary to install also sequence of installation CD in the electrical network of electric power systems. The analysis on the basis of factor design of experiments can be for this purpose used. Thus in the capacity of factors powers CD in various, most probable load buses with the greatest factors of a reactive power can be used.

The regression equation will have the following appearance:

$$\bar{Y} = f(\vec{X}) = b_0 + \sum_{i=1}^{k} b_i X_i \qquad (4)$$

Where, $\bar{Y}$ – average meanings of the sized up parameter; X_i – current meanings of input parameters; b_0, b_i – estimations of factors of the equation of a regression.

Table 1

Outcomes of accounts of sampling CD and performances of their efficiency in PC electric power systems

$Q_{K\Sigma}$	Q_{Ki}, MVAr							ΔP	ΔΔP	$\Delta\Delta W_{year}$, kVt.h		$C_{\Delta\Delta W}$, a dale	
	$Q_{k\,I}$	$Q_{K\,II}$	$Q_{k\,III}$	$Q_{k\,IV}$	$Q_{K\,V}$	Q_{kVI}	$Q_{k\,VII}$	MVt	MVt	τ=4500	τ=5000	1	2
0	0	0	0	0	0	0	0	127,38	-	-	-	-	-
142	18	18	18	25	19	20	24	123,78	3,60	16200000	18000000	810000	900000
158	20	16	16	30	16	30	30	123,53	3,85	17325000	19250000	866250	962500
180	20	20	20	30	20	40	30	123,16	4,22	18990000	21100000	949500	1055000
194	20	20	24	40	20	40	30	123,01	4,37	19665000	21850000	983250	1092500
235	25	25	25	45	25	45	45	122,09	5,29	23805000	26450000	1190250	1322500
255	35	30	30	50	25	50	35	122,05	5,33	23985000	26650000	1199250	1332500

Table 1 prolongation

C_{CD}, in USD		$E_y=C_{\Delta\Delta W}-(C_{cd}/n)$, in USD				$T_{pb}=C_{CD}/C_{\Delta\Delta W}$, year			
15000	20000	1	2	3	4	1	2	3	4
-	-	-	-	-	-	-	-	-	-
2130000	2840000	668000	758000	620667	710667	2,6	2,4	3,5	3,2
2370000	3160000	708250	804500	655583	751833	2,7	2,5	3,6	3,3
2700000	3600000	769500	875000	709500	815000	2,8	2,6	3,8	3,4
2910000	3880000	789250	898500	724583	833833	3,0	2,7	3,9	3,6
3525000	4700000	955250	1087500	876917	1009167	3,0	2,7	3,9	3,6
3825000	5100000	944250	1077500	859250	992500	3,2	2,9	4,3	3,8

The greatest and least meanings of factors can make (0,15-0,35) P_{max}. Annual economic efficiency and pay-back period application CD will be responses (outcomes). The sequence will be defined on positive greatest regression coefficient for annual economic efficiency and on negative greatest factor for pay-back period. On these in factors it is possible to choose as sequence, and most an effective value of power CD.

For sampling of sequence of installation CD in the real electrical network *110 kV* electric power systems have been carried out also researches on disposing CD in 12 knots resulted in table 2.

Table 2

Outcomes of indications on active and a reactive power for separate substations

№	SS	P_{max} MVt	Q_{max} MVAr	tg φ	P_{min} MVt	Q_{min} MVAr	tg φ
1	SS № 17	121,15	76,86	0,63	104,86	47,01	0,45
2	SS № 162	111,72	57,25	0,51	32,38	9,01	0,28
3	SS № 9	252,86	85,75	0,34	38,03	87,57	2,30
4	SS № 195	159,34	72,48	0,45	49,16	17,32	0,35
5	SS № 298	87,44	44,17	0,51	67,88	37,12	0,55
6	SS № 290	194,31	81,89	0,42	43,97	16,82	0,38
7	SS № 99	163,63	52,33	0,32	29,37	13,94	0,47
8	SS № 26	194,41	64,72	0,33	28,06	46,51	1,66
9	SS № 23	93,19	36,78	0,39	28,5	31,13	1,09
10	SS № 112	73,92	32,14	0,43	12,24	5,05	0,41
11	SS № 31	64	32	0,50	25	14,07	0,56
12	SS № 21	106,3	81,97	0,77	139,6	40	0,29
THE SUM:		1378,05	572,23	0,42	599,05	365,55	0,61

The plot of a fractional factorial experiment of type $2^{12-8}=16$ is made. Following adequate equations of a regression are gained:

$$\Delta\Delta P = 7{,}75 + 0{,}514X_7 + 0{,}180X_5 + 0{,}149X_2 + 0{,}146X_9 + 0{,}139X_3 +$$
$$+ 0{,}131X_8 + 0{,}110X_{11} + 0{,}105X_{10} + 0{,}104X_6 + 0{,}101X_1 + 0{,}080X_{12} + 0{,}066X_4 \quad (MVt)$$
$$\Delta\Delta W = 38{,}753 + 2{,}571X_7 + 0{,}903X_5 + 0{,}746X_2 + 0{,}734X_9 + 0{,}696X_3 +$$
$$+ 0{,}659X_8 + 0{,}553X_{11} + 0{,}528X_{10} + 0{,}521X_6 + 0{,}509X_1 + 0{,}403X_{12} + 0{,}334X_4 \quad (\text{mln.kVt.h})$$
$$E_{ann} = 1{,}47 + 0{,}108X_7 + 0{,}035X_5 + 0{,}024X_2 + 0{,}023X_9 + 0{,}021X_3 +$$
$$+ 0{,}019X_8 + 0{,}019X_{10} + 0{,}014X_{11} + 0{,}012X_1 + 0{,}006X_6 + 0{,}006X_{12} + 0{,}003X_4 \quad (\text{мln.dol.})$$
$$T_{pb} = 3{,}587 + 0{,}100X_6 + 0{,}062X_{12} + 0{,}050X_1 + 0{,}050X_4 + 0{,}050X_{11} +$$
$$+ 0{,}037X_2 + 0{,}037X_3 + 0{,}037X_8 + 0{,}025X_9 + 0 \cdot X_{10} - 0{,}012X_5 - 0{,}087X_7 \quad (\text{year})$$

From the analysis of equations E_a and *the Current* follows the following sequence of installation CD in knots: 7-5-2-9-3-10-8-11-1-12-4-6.

V. ANALYSIS CRC IN A TYPICAL SUPPLY NET

The typical electric radial supply net *110/10/0,4 kV* is observed (fig. 2), in which buses *110 kV* are a feeding knot of an electric-power supply, and transformer T*1 (110/10 kV)*, a line *10 kV* and transformer *T2 (110/10 kV)* belong to a supply net. Summarized loading of users makes

25+j11,5MVA, distributed between knots *1 (0,4 kV)*, *2* and *3 (10 kV)*. Equivalent parameters of lines and transformers are resulted in table 3.

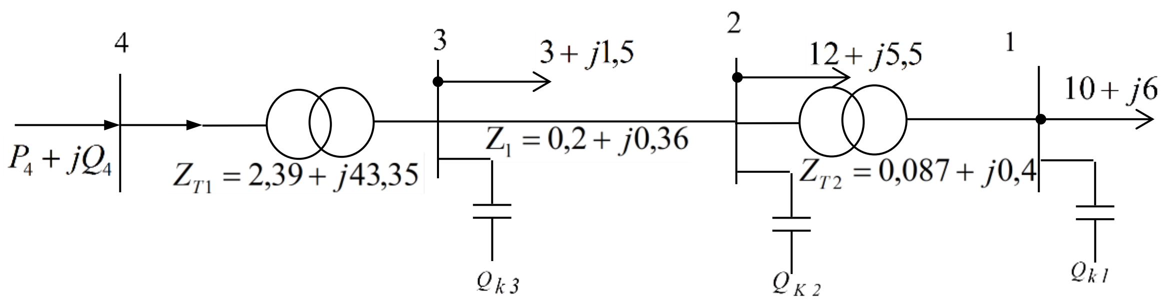

Fig. 2. The circuit design observed typical SS

Table 3

Equivalent parameters of lines and transformers

Net element	Type, brand	S, MVA	I, A	R_{ekv}, Om	X_{ekv}, Om
Tr-r T1	2xTDN 16/110	2x16=32		2,19	43,35
Tr-r T2	8xTM 1,6/10	8x1,6=12,8		0,0875	0,41
Line	4xAC-120		4x390=1560	0,21	0,358
Loading					
S_1		10 - j6			
S_2		12 - j5,5			
S_3		3 - j1,5			

Outcomes of account before and after CRC in the distributive electrical network of electric power systems are resulted in table 4.

Table 4

Outcomes of account before and after CRC in the distributive electrical network

Indexes	Before compensation	After compensation				Efficiency of compensation			
		1	*2*	*3*	*4*	*1*	*2*	*3*	*4*
ΔP_{T2}	0,119	0,119	0,119	0,119	0,088	0	0	0	0,031
ΔQ_{T2}	0,556	0,556	0,556	0,556	0,413	0	0	0	0,143
ΔP_{T1}	0,157	0,121	0,118	0,119	0,117	0,039	0,038	0,038	0,04
ΔQ_{T1}	3,115	2,388	2,33	2,358	2,32	0,727	0,785	0,757	0,795
ΔP_l	1,33	1,33	1,036	1,132	1,032	0	0,294	0,198	0,298
ΔQ_l	2,28	2,28	1,77	1,934	1,763	0	0,51	0,346	0,517
$\sum I_{add}$	1560	1560	1560	1560	1560				
$\sum I_l$	1456	1456	1284	1342	1281	0	172	114	175
U_1	356	366	390	382	398	10	34	26	42
S_{T1}	32,66	27,68	27,7	27,51	27,28	4,98	4,96	5,11	5,38

S_{T_2}	12,05	12,05	12,05	12,05	10,2	0	0	0	1,75
$\sum \Delta\Delta P$ *MVt*						0,039	0,332	0,236	0,369
$\sum_{\Delta\Delta W} = \sum_{\Delta\Delta} P \cdot \tau \cdot 10^3$ кVt.h. $(\tau = 4500)$						177,5	1494	1062	1660
$C_{\Delta\Delta W} = \sum_{\Delta\Delta} W \cdot \beta \cdot 10^3\, dol.$ $\left(\beta = 0{,}07 \frac{dol}{кVt.h}\right)$						12,42	104,58	74,34	116,23
$C_{CD} = C_{ко} \cdot Q_k \cdot 10^3\, dol.$ $\left(C_{ко} = 20 \cdot 10^3 \frac{dol.}{MVAr}\right)$						200	200	200	200
$Э_y = \left(C_{\Delta\Delta W} - \frac{C_{CD}}{n_1}\right) \cdot 10^3\, dol.$ $(n_l = 10\, year)$						-7,58	84,6	54,34	96,2
$T_{pb} = \frac{C_{CD}}{C_{\Delta\Delta W}}$ *year*							1,93	2,6	1,72

It is observed following alternatives of disposing CD in knots:

1) $Q_{K3} = 10{,}5\, MVAr$
2) $Q_{K2} = 10\, MVAr$
3) $Q_{K3} = 5 MVAr \quad Q_{K2} = 5\, MVAr$
4) $Q_{K2} = 5\, MVAr \quad Q_{K1} = 5\, MVAr$

From the analysis of outcomes of account follows, that in a typical supply net *10-0,4 kV* on everyone installed *1MVAr* BSC the economy on losses (100-160 thousand *kVt.h* is gained. The electric power in a year, with pay-back period BSC 2-2,6 years. Thus, loading of transformers decreases more than on 15 %, and lines on 12 %. Voltage levels in the most remote knot raises on 7-11 %. The Most effective is installation CD more close to users, especially on voltage 0,4 sq. Installation CD in the accepted level will ensure system of an electric-power supply of a supply net with necessary economic power in a knot of association of a supply net, with *tgφ=0,21* which before compensation made *tgφ=0,6*. Installed in supply net CD makes, $\frac{10 MVAr}{25 MVt} = 0{,}4 \frac{MVAr}{MVt}$ that matches to an average value of equipment CD for supply nets.

VI. CONCLUSIONS

1. On the basis of technical-and-economic indexes and investment possibilities of an electric power system it is given a technique of sampling and disposing of devices a reactive power compensation in the distributive electrical network, raising effectiveness and regime reliability of electric power systems at the expense of decrease of losses of the electric power.

2. For reaching of the greatest efficiency it is installed sequence of installation CD in the electrical network of electric power systems with use of the analysis on the basis of factor design of experiments and the adequate equations of a regression for parameters of efficiency CRP are accordingly gained. From the analysis of the matching equations are defined sequence of installation CD in 12 knots of electric power systems.

3. Outcomes of implementation of the offered technique for a typical supply net has shown, that on everyone installed *1MVAr* BSC the economy on 100-160 thousand losses *kVt.h* is gained. The electric power in a year, with pay-back period BSC 2-2,6 years. Installed in supply net CD makes, $0{,}4 MVAr/MVt$ that matches to an average value of equipment CD for supply nets.

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