COMPARISON OF FLEXIBLE SYSTEMS FOR COMPENSATION OF REACTIVE POWER

ELASTĪGĀS REAKTĪVĀS JAUDAS KOMPENSĒŠANAS SISTĒMU SALĪDZINĀJUMS

J.Zakis, I.Rankis, A.Zhiravetska

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Introduction

Compensation of reactive power is still actual in many enterprises, where load is changing very fast with time. It means that there is a necessity for flexible reactive power compensation system that could regulate balance of reactive power fast and smooth. We can get such regulation using combined LC compensation system [1], where reactor current is regulated with a thyristor regulator, but capacity of capacitors is constant. Besides this there is one more possible solution where LC elements are used together with modulated rectifier [2].
It is possible to realize both variations and they provide flexible compensation of reactive power and high-speed operation. The point and task of this paper is to compare technical parameters of such systems.

Thyristor regulated parameters of LC system.

There is a smooth regulation system of reactive power with thyristor regulated reactors and capacitors with constant capacity [1] depicted in fig.1.

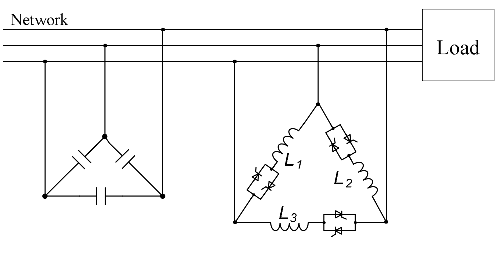

Fig.1. Smooth regulation system of reactive power with thyristor regulated reactors

As we can see in fig.1, there is capacitor and reactor in each phase. Capacity of capacitor is accepted constant and it corresponds to maximal compensating lagging power of load, i.e. $Q_C = Q_{LD\max}$. If consumed reactive power of load is decreasing in procession, then reactors are regulated in order to decrease total reactive power. Total reactive power of reactors is

$$Q_{L\max} = k_R \times Q_C \tag{1}$$

where k_R defines necessary dimensions and costs.
Common minimal reactive power of compensation system is

$$Q_{k\min} = Q_C(1 - k_R) \tag{2}$$

Depending on ratio minimal power and nominal Q_C, parameters of reactors will change. Approximate weight of reactor is [3]

$$G_L \approx 3I_L^2 L \tag{3}$$

where in delta connection of reactors

$$Q_{L\max} = k_R Q_C = \sqrt{3}U_l\sqrt{3}\frac{U_l}{\omega L} = 3\frac{U_l^2}{\omega L} \tag{4}$$

From here we can get inductance for one reactor

$$L = \frac{U_l^2 3}{k_R Q_C \omega} = 3\frac{U_l^2}{k_R Q \omega} \tag{5}$$

Effective current of reactor

$$I_{Lef} = \frac{U_l}{\omega L} = \frac{U_l k_R Q_C \omega}{\omega U_l^2 3} = \frac{k_R Q_C}{3U_l} \tag{6}$$

Finally the total weight of all reactors of the system

$$G_L \approx 3\frac{k_R^2 Q_C^2 \times 3U_l^2}{9U_l^2 k_R Q_C \omega} = \frac{Q_C k_R}{\omega} \tag{7}$$

Accepting different k_R values from 0,5...1, we can get necessary weight depending on maximal compensating reactive power Q_C. (fig.2.).

Table 1.
The weight of reactors (kg) at different powers of compensators

	k_R			
Qc, kvar	**0,5**	**0,7**	**0,9**	**1**
20	32	45	57	64
40	64	89	115	127

60	96	134	172	191
80	127	178	229	255
100	159	223	287	318

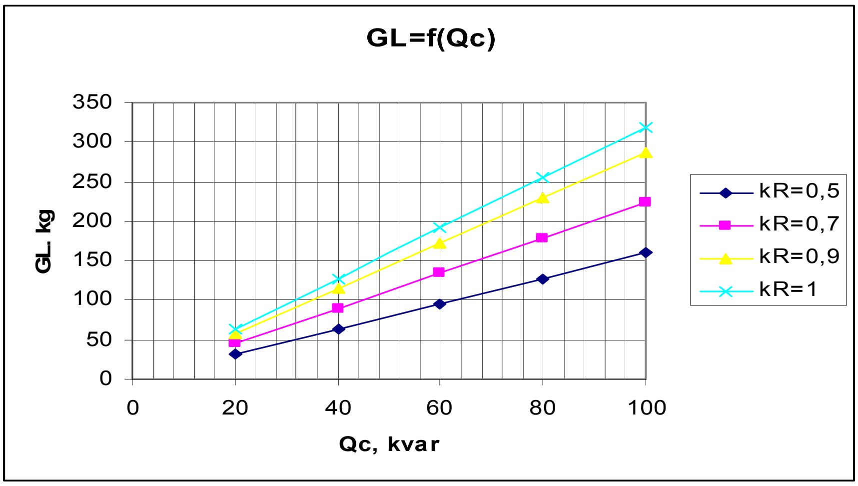

Fig.2. Weight of reactors depending on power of compensator at different k_R

As we can see in fig.2, the weight of compensation reactors grows in almost direct ratio to reactive power.
The second element in compensation system is capacitor the reactive power of which is Q_C. From available data of capacitors there are system parameters for different values of reactive power given in table 2.

Table 2.

Parameters of compensation capacitors

Type	Capacitors, kvar	Steps	Current, A	dimensions	G_C, kg
Reactive power compensation devices with step 2,5 kvar					
AKVS-22,5	2,5+5+5+5+5=22,5	1.2.2.2.2.	35	500x500x200	17,2
AKVS-37,5	2,5+5+10+20=37,5	1.2.4.8.	56	600x600x300	28,6
AKVS-57,5	2,5+5+10+(2x20)=57,5	1.2.4.8.8.	86	800x600x300	44
AKVS-77,5	2,5+5+10+(3x20)=77,5	1.2.4.8.8.	115	1000x600x300	59,2
Reactive power compensation devices with step 3,33 kvar					
AKVS-22,5	3,33+6,67+12,5	1.2.4.	34	500x500x200	17,2
AKVS-35	3,33+6,67+12,5+12,5	1.2.4.4.	52	600x600x300	26,8
AKVS-72,5	3,33+6,67+12,5+(2x25)	1.2.4.8.8.	107	1200x800x300	55,4
AKVS-97,5	3,33+6,67+12,5+(3x25)	1.2.4.8.8.	143	1200x800x300	74,4

Modulated compensators of reactive power

With modulation, which is realized in diod-transistor rectifier with C load in DC side (fig.3.), it is possible to maintain quasi sinusoidal current, that leads or lags behind network voltage for angle 90°.

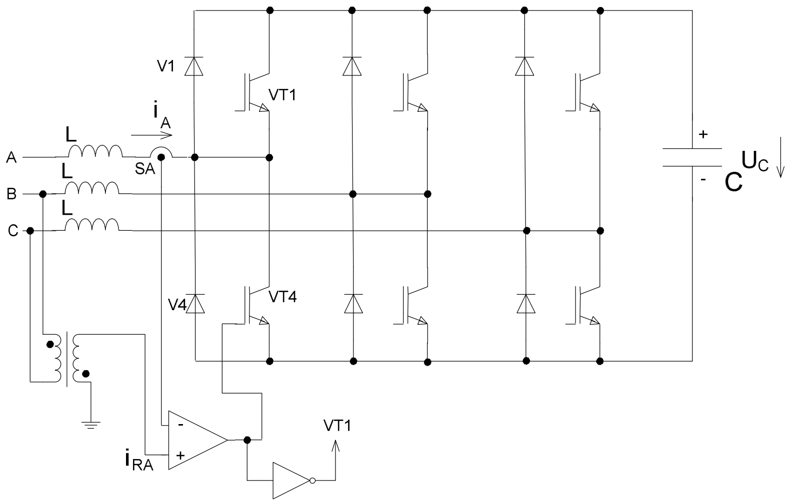

Fig.3. Scheme of modulated compensator of reactive power

Also in this scheme there is LC compensation unit, but regulation of reactor current is realized switching reverse transistors of full bridge rectifier each shoulder accordingly to reference between reference phase current and the real one.

The algorithm of regulation is:

- If real current of the phase, which measured with sensor (fig.3. in phase A there is sensor SA) is bigger than reference signal i_{RA} of phase Au (in scheme it is acquired proportional on 90 to leading voltage U_{CB}, t.i., compensator works with leading current), then transistor VT1 is switched on and capacitor voltage works against i_A increment;
- If real phase current i_A is smaller than i_{RA}, then VT4 is switched on. As a result capacitor C voltage contributes growth of i_A.

Accordingly current i_A fluctuates near sinusoidal curve of the referent instantaneous value. For determination in system we can initiate an element, which maintains fluctuations in constant level ΔI_1. If the upper transistor is switched on then differential equation is

$$U_{Am} \sin \omega t - 0{,}5U_C = L\frac{di}{dt} \tag{8}$$

but when lower transistor is switched on,

$$U_{Am} \sin \omega t + 0{,}5U_C = L\frac{di}{dt} \tag{9}$$

If ΔI_1 in both regimes is constant then equal growth and drop decrease times of the current in switching period $U_{Am} \sin \omega t = 0$. Then there will be the highest switching frequency of transistors

$$f_{\max} = \frac{U_C}{4L\Delta I_1} \quad (10)$$

This equation also can be used as calculation of input reactor L using reference f_{max}. That is limited by power loses of transistor dependence on switching frequency. Accordingly

$$L \geq \frac{U_C}{4f_{\max}\Delta I_1} \quad (11)$$

Voltage value of capacitor in steady state regime is approximately equal with input line voltage amplitude of the rectifier bridge. Capacitor voltage at input current offset of phase on 90° is

$$U_C \approx \sqrt{2}U_l + \sqrt{3}I_{1m}\omega L \quad (12)$$

where I_{1m} is amplitude of the reactor current which is connected with compensating reactive power.
As a result

$$U_C \approx \sqrt{2}U_l + \frac{Q\sqrt{2}}{U_l}\omega L \quad (13)$$

or, noticing L expression,

$$U_C = \frac{\sqrt{2}U_l^2 4f_{\max}\Delta I_1}{4U_l f_{\max}\Delta I_1 - \sqrt{2}Q\omega} \quad (14)$$

As we can see, to get normal operation

$$f_{\max}.\Delta I_1 > \frac{\sqrt{2}Q\omega}{4U_l} \quad (15)$$

It means, if Q grows, ΔI1 must be increased, because increasing of f_{max} is not possible because of the power loses of transistor commutation.
Accepting, that ΔI_1 is connected with Q whereby

$$\Delta I_1 \approx \frac{Q}{4\times 10^3} \quad (16)$$

Then frequency must be

$$f_{max} > \frac{\sqrt{2}\omega 10^3}{U_l} = f^* \quad (17)$$

At U_l=380V, ω=314 1/s this parameter f^*=1173 Hz.
In Fig. 4 and 5 from the gained expressions is depicted L=f(Q), U_C=f(f) at different f_{max} and ΔI_1 values. It is assumed that, that ΔI_1 value is connected with Q value: the bigger is Q, the bigger can be ΔI_1.
In fig. 4.is depicted U_C=f (f_{max}) at different $k_f=f_{max}/f^*$=2, 3, 4.

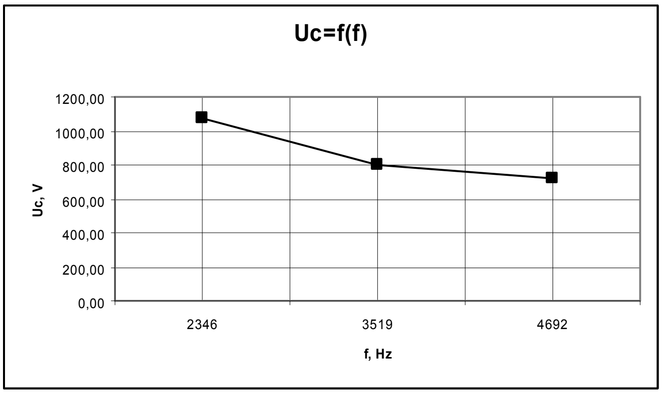

Fig.4. Capacitor voltage at different transistor modulating frequencies f_{max}

As we can see in fig. 4 capacitor voltage U_C of compensator depends on maximal control frequency f_{max} of transistor that depends on modulated current difference ΔI_1 of transistor.
At the previous assumptions inductance of reactor is

$$L = \frac{\sqrt{2}U_l^2}{Q(U_l k_f f^* 10^{-3} - \sqrt{2}\omega)} \quad (18)$$

And from this expression in fig.5 inductance L values depends on reactive power Q.

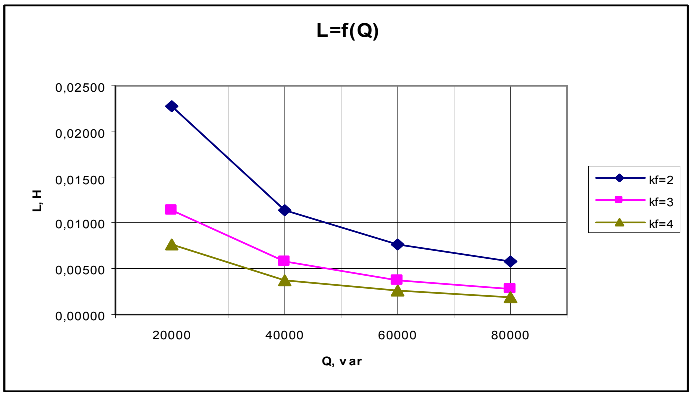

Fig.5. Reactor inductance at different reactive powers of reactors and frequencies

As we can see necessary inductance L depends on reactive power and frequency. The smaller reactive power the bigger is inductance L. Similarly L is growing with decreasing of frequency. The common weight of reactors in compensator can be expressed as [3]

$$G_L \approx L\frac{Q^2}{U_l^2} \tag{19}$$

modifying, $$G_L = \frac{\sqrt{2}Q}{(U_l k_f f * 10^{-3} - \sqrt{2}\omega} \quad . \tag{20}$$

According to this expression calculated weight of reactors depending on Q at different maximal frequencies are depicted in fig. 6.

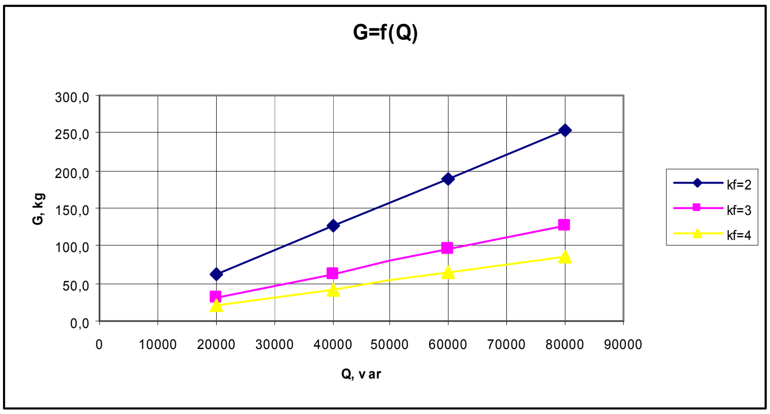

Fig.6. The common weight of reactors depending on reactive power and maximal frequency

As we can see, reactor weight grows almost proportionally to reactive power of compensator; however at higher frequencies weight is smaller. If comparing reactor weight at $f^*=2$ (f_{max}=2,35 kHz, which is optimal) with reactor weight in scheme with thyristor regulated reactors in fig.2. Here at Q=80 kvar the weight is 255 kg which is equal with reactor weight in 1st scheme at k_R=1. But in the scheme with regulated reactors k_R can be smaller than 1 and then reactor weight in 1st scheme will be smaller than in the modulated rectifier scheme.
Modulation type compensator capacitor is uni-polar and it works with small voltage ripple which accordingly to theory of three-phase full-bridge rectifier [4] is with relative ratio versus U_C amplitude 0,057 and frequency 300 Hz (if network frequency is 50 Hz). In addition capacity of capacitor must provide this ripple with amplitude of phase current during time interval T/2 (full increment time interval

$$C \geq \frac{I_{1m}}{12 \times f \times 0{,}057 \times 2 \times U_C} \; . \tag{21}$$

Such reactive power of capacitor is rather small

$$Q_C = C \times 12 \times \pi \times f \frac{0{,}057^2 U_C^2}{2} \; . \qquad (22)$$

It is much smaller than reactor necessary reactive power therefore we can accept, that main reactive elements in compensator are reactors. For example, at Q=20000 var (I_{1m}=43.2 A) and U_c=1070 V necessary C=590 μF. Reactive power of this capacitor is 2068 var. It means that weight of capacitor; dimensions and costs are smaller than reactors in modulated scheme.

Conclusions

1. Compensator where thyristor regulated LC system parameters are used, power of capacitors, weight and capacity are bigger than in modulated compensator of reactive power.
2. Modulated compensator capacitor voltage U_C depends on maximal control frequency f_{max} of transistors, which must be connected with transistor modulated reactor current difference ΔI1. The bigger is f_{max}, the smaller is compensator capacitor voltage U_C.
3. The weight of reactors of compensation system with regulated reactors depends on minimal compensated reactive power. The weight of modulated reactor compensator depends on compensator reactive power and maximal frequency.
4. Comparing both compensation systems it is visible that reactor weight, if only in regulated reactor system capacitor power must be fully compensated, but in modulated system maximal frequency is not forced, are almost the same at appropriate reactive power Q. It means that both systems according to reactor parameters are equal evaluated and as uppermost must bee considered other parameters – control systems, costs of semiconductor switches and other.

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Janis Zakis, Ph.D student
Riga Technical University, Institute of Industrial Electronics and Electrical Engineering
Address: b.Kronvalda 1, LV-1048 Riga, Latvia
Phone: 371+7089917

e-mail: janis_zakis@one.lv

Ivars Rankis, professor, Hab.Dr.sc.eng.
Riga Technical University, Institute of Industrial Electronics and Electrical Engineering
Address: b.Kronvalda 1, LV-1048 Riga, Latvia
Phone: 371+7089917
e-mail: rankis@rtu.eef.lv

Anastasija Zhiravetska, asoc. prof., Dr.sc.eng.
Riga Technical University, Institute of Industrial Electronics and Electrical Engineering
Address: b.Kronvalda 1, LV-1048 Riga, Latvia
Phone: 371+7089916
e-mail: ziravecka@rtu.eef.lv

Zaķis J., Raņķis I., Žiravecka A. Elastīgās reaktīvās jaudas kompensēšanas sistēmu salīdzinājums.
Darbā ir aplūkots divu reaktīvās jaudas kompensēšanas sistēmu tehnisko parametru salīdzinājums. Shēmai ar tiristoru vadāmajiem reaktoriem ir lielāki gabarīti, jo nepieciešamie kondensatori ir visās trijās fāzēs. Turklāt maiņstrāvas kondensatoru gabarīti ir lielāki nekā līdzstrāvas kondensatoriem. Shēmā ar modulējamu reaktīvās jaudas kompensatoru reaktīvo elementu skaits spēka shēmā ir mazāks, jo ir nepieciešams tikai viens kondensators taisngrieža izejā.
Kompensācijas sistēmu droseļu masas abām sistēmām ir gandrīz vienādas, ja vien modulējamā kompensācijas sistēmā netiek forsēta maksimālā frekvence. Tas nozīmē, ka, izvēloties kompensēšanas sistēmu kādam objektam, var balstīties uz citiem parametriem – vadības sistēmas, pusvadītāju slēdžu cenas u.c. Modulējama taisngrieža shēmā droseles nepieciešamā masa ir atkarīga ne tikai no kompensatora jaudas, bet arī no frekvences.
Lai vienkāršāk būtu izvēlēties kompensēšanas sistēmu elementu tehniskos parametrus, tiek piedāvātas tuvinātas to aprēķinu izteiksmes.

Zaķis J., Raņķis I., Žiravecka A., Comparison of flexible systems for compensation of reactive power.
The paper concerns technical parameters of two reactive power compensation systems – with thyristor-regulated reactors and with a modulated reactive power compensator. The former possesses larger sizes since there are capacitors in each of the three phases. Besides, the sizes of AC capacitors are larger than those of DC capacitors. In the scheme with a modulated reactive power compensator the number of reactive elements is smaller, because only one capacitor is needed at the output of a full-bridge rectifier. The weight of reactors in both systems is approximately equal unless in a modulated compensation scheme the maximum frequency is forced. This means that in deciding on a particular compensation system for an object we can choose among other factors –the control system, the cost of semiconductor switches, etc.
The weight of reactors in a modulated full-bridge rectifier scheme depends not only on the compensator power but also on the operating frequency.
The authors give approximate expressions that simplify the calculation of technical parameters of the compensation systems.

Закис Я., Ранкис И., Жиравецкая А., Сравнение гибких систем компенсации реактивной мощности.
В работе рассмотрены две системы компенсации реактивной мощности и их сравнение. Схема с реакторами, управляемыми тиристорами, имеет большие габариты, т.к. конденсаторы установлены во всех трех фазах. Кроме того габариты конденсаторов переменного тока больше нежели постоянного тока. В силовой схеме с модулируемым компенсатором реактивной мощности количество реактивных элементов меньше, т.к. необходим только один конденсатор на выходе схемы. Масса дросселей системы компенсации для обеих систем практически одинакова, если только в модулируемой системе компенсации не форсируется максимальная частота. То есть выбирая систему компенсации для какого-то объекта, можно руководствоваться другими параметрами – схема управления, стоимость полупроводниковых ключей и т.д.