Original Scientific paper
UDK 621.352:[53.082.75:537.311.31
DOI: 10.7251/afts.2021.1324.009B
COBISS.RS-ID 132375297

PARAMETRIC OPTIMIZATION OF THE STRUCTURE OF CONTROLLED HIGH-VOLTAGE CAPACITOR BATTERIES

Babenko Vladimir[1], Danilov Alexandr[1], Vasenin Dmitrii[1], Krysanov Valery[1]

[1]Voronezh State Technical University, Voronezh, Russia, e.mail: vasenindmitrij31@yandex.ru

ABSTRACT

The article considers the issues of increasing energy efficiency of 6-10 kV controlled capacitor plants of power supply systems of energy-intensive facilities due to more accurate compensation of reactive power. Analysis of the most common circuits for connecting batteries of static capacitors using semiconductor and electromechanical switches was carried out.

The feasibility of using a simplified approach of determining the optimal structure of the power part of high-voltage plants for compensation of reactive power according to the criterion of minimum cost and minimum level of electric energy losses is determined. The possibility of parametric optimization of high-voltage capacitor batteries to higher voltage levels is shown, taking into account the given specific requirements of these electric power facilities.

Key words: *controlled batteries of static capacitors, semiconductor and electromechanical switches, power factor compensation, connection circuit*

INTRODUCTION

In response to constant increase of electricity cost and appearance of new sophisticated controls of power supply system, industrial enterprises, immediacy of energy saving problems trends upward [1]. It is worth noting that distribution systems (0.4 kV – 35kV) that constitute over 70% of national power industry scope are of outstanding interest. National average level of power loss not related to net active power consumption is above 8-12% of total volume of 6-10 kV power grid.

This level significantly increases as reactive power circulation in power supply system grows. For instance, power factor increase from 0.35 to 0.8 causes losses increase by 10-14%. Taking this into account, standard recommendation is to maintain power factor in general industrial power supply system equal or less than 0.4 [2]. So, one of the most popular ways is wide use of different means and methods of power factor compensation (PFC).

Now industrial power supply systems (main power consumer), housing and utilities, agro-industrial sector need significant increase of power factor compensation (PFC) both of local (RFC of low voltage) and centralized type (PFC of high voltage). The method is determined taking into account multifactor estimation of power supply system structure, operation modes, and type of power consumers and technical parameters of RFC means. On the one hand, if local method of PFC is used, both high and low voltage networks are relieved from reactive currents (so that effect of power losses decrease is more significant) and cost factor (per 1 kVAr) of low voltage equipment is higher.

On the other hand, if centralized method of PFC is used, only high voltage networks are relieved from reactive currents (thus, effect of power losses decrease is less significant) and cost factor (per 1kVAr) of low voltage equipment (in particular, power capacitors) is higher. So PFC efficiency depends largely on multiple characteristics of reactive power controls, such as price, reliability, regulation band and regulation smoothness, response speed, multifunctionality, weight-size parameters. Multiple classification analysis of operating and developing PFC systems [3,4,5,6,7] provides opportunity to argue that nowadays controlled static capacitors batteries are the optimum option for industrial distribution power supply systems [8].

METHODS AND MATERIALS

Object Efficiency and scope of application of abovementioned structures of PFC means is being determined to a large extent by the way and means of static capacitors batteries connection to the grid. They mostly determine their technical and economic performance. As a rule, depending on the voltage in considered power distribution systems electromagnetic contactors (0.4 kV-10kV), vacuum switchers (6 kV-10kV), thyristor keys (0.4 kV-10kV) can be used as switching elements.

Significant enlarging of scope of application of thyristor keys instead of electromechanical ones is caused by significant increase of individual loads of alternate type, that are requiring for dynamic PFC. Despite the fact that type of total load on high voltage buses as a rule is more equal, required level of power supply losses decrease can be reached by using fast thyristor switch (e.g.: manufacturer Beluk, BEL-TS H2; DSTM3 Lovato; TSM-LC and TSM-HV Epcos AG).

In such a case issues related to main disadvantaged of electromechanical switching elements of static capacitors are resolved: increased operating costs (constant maintenance service); slow response (pauses between two switching ons exceed 30 seconds to provide batteries discharge): low level of electromagnetic tolerance (when switching static capacitors batteries significant overvoltage is possible, and then resonance phenomenon); reliability (constant operation of contactors with shock breakover current and capacitors with overvoltage during switching offs).

Special system of thyristor keys control ensures fast response at a level of 20-30 ms and static capacitors batteries connection to the grid excluding shock current loads and overvoltage [9]. For instance, control system of thyristor capacitor units ‘Epcos AG’ is based on BR6000-T or Prophi-T reactive power controllers.[10,11]. The system ensures reliable algorithm of switching on anti-parallel thyristor keys in phases of contactors TSM-AT, TSM-HV50.

Fast response of control system and special low-value discharge resistor EW-22 ensure simultaneous connection of any number of static capacitors batteries sections [10,11,12]. At the same time following is being indicated: phases voltage on a contactor, malfunction of charge exchange unit, temperature monitoring, voltage monitoring and operable condition of capacitors connected. All of this drastically increases time of reliable operation of capacitors batteries.

Taking into consideration guaranteed mean time to failure of semiconductor power components, service life of thyristor capacitors units is estimated at 10-15 years.

However, it should be noted that with all advantages of PFC means of this kind, there are two factors that prevent their wide use in 6-10 kV grids:

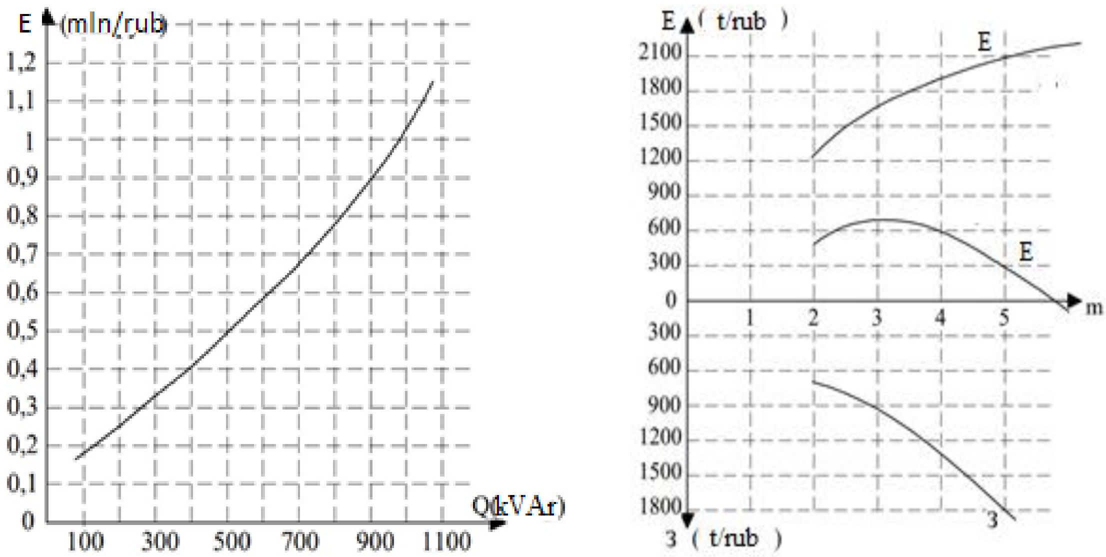
- due to technical characteristics of modern semiconductor devices (thyristors, bilateral triode thyristors) it becomes necessary to make series (SCR units) designed for high voltage
- separate set of expensive thyristor switch is required for every static capacitors battery to connect

All of this drastically complicates high voltage thyristor unit and raises the price of it. At the moment therefore controllable static capacitors based on vacuum switchers are wider spread in industrial 6-10 kV power supply systems.

PFC units for voltage of 6-10 kV have regulation band from 150 kVAr to 6 mVAr (regulation accuracy is 75-750 kVAr), longer lasting service life. For example, in VARNET units vacuum switches BB/TEL-10/20-1000 are used as switching devices.

Vacuum switchers VVNR-10/630 or vacuum contactors KVT-10 are used in power factor correction units made by ‘Matik-electro’. Average commutation life (at nominal current value) of such switchers is not above 10000 on-off cycles and price is in the range from 65,000 to 125,000 rubles.

Research of market of modern PFC units for 6-10 kV shows that average price of PFC units is nonlinear dependence (close to power function) on static capacitors battery capacity, FIgure 1.



a) b)

Fig.1. Functional dependences of price (a) and averaged efficiency (b) of high voltage PFC units use.

With consideration to high price of switching elements for static capacitors batteries connection, maximum energy efficiency is only possible if the best possible combination of switching elements and structure (connection pattern) of controllable PFC units. Normally, price of high voltage reactive power compensation units is determined in accordance to the customer’s technical requirements specification: power supply system parameters, load curves, regulation band and regulation accuracy of reactive power.

At the same time implementation of an option with minimal number of sections of capacitors batteries and switching elements is preferable. In this vein one may be limited to consideration of the most widely spread connection patterns of power part of industrial reactive power compensation unit: direct connection circuit of one-and multiple section batteries with equal and unequal sections power; ‘delta-star’ switching circuit; two-section static capacitors battery connection circuit with a midpoint; ‘polygonal’ capacitors connection circuit [13,14,15,16].

At the same time, it is reasonable to take minimal number (minimal price respectively) of switching elements and section capacitors upon the given regulation band and regulation accuracy of reactive power as optimal structure criterion. Then functional relation between PFC specific economic efficiency (rub/kVAr) and number of section (steps) of control of selected connection patterns.

RESULTS AND DISCUSSION

Considering the complexity of formalizing of such multifactorial problem in analytical form, it is advisable to solve this problem using a simulation calculation in the Matlab environment by varying the voltage level of the load node U_0 and calculating the values of additional active power losses and PM values corresponding to this voltage, taking into account the constraints [17].

The proposed step sequence of calculations is shown below:

1. The initial parameters of the considered load node of the power supply system (P_0, Q_0, U_0) are set, the voltage of the supply feeder Uc, which will be considered unchanged.

2. The voltage values of the load sub-nodes (n groups of consumers) U_0 (n) in the voltage segment are determined (for example, 0.95 Un - 1.1 Un with a step of 1V.

3. For each value $U_0(n)$, the value of the active system current $I_{oa}(n)$,), the reactive current of the system $I_{0p}(n)$, the active power of the system $P_0(n)$, the reactive power of the system $Q_{op}(n)$ and the total losses of the active power of the system $\sum \Delta P(n)$ are calculated.

   Reactive power by load groups is defined as:

$$Q_{0n}(n) = \sum (\mu_{iAM}(n) Q_{iAMN} + \mu_{iSM}(n) Q_{iSMN})$$

   Where, μ_{iAM}, μ_{iSM} relative reactive power by groups of asynchronous motors, synchronous motors

   Q_{iAMN}, Q_{iSMN} - total rated reactive power by groups of consumers of the subassembly

$$I_{oa}(n) = \frac{P_0(n)}{\sqrt{3} U_0(n)}$$

$$I_{opn}(n) = \frac{Q_{0n}(n)}{\sqrt{3} U_0(n)}$$

   When calculating the reactive component of the current of the subunits $I_{op}(n)$ at a voltage of $U_0(n)$, we assume that the excitation current of all synchronous motors is constant.

   Total active power losses of the entire load node $\sum \Delta P(n)$ are determined by:

$$\Delta P = \sum_{i=1}^{n} \Delta P_i \, f\left(K_U, K_{0i}, \beta_i\right)$$

   where ΔP_i - additional power losses at the rated mode of the i-th technological equipment, kV

   K_U, K_{0i}, β_i - values of the relative magnitude of the voltage, the coefficient of simultaneity and the load of the i-th technological equipment

4. Taking into account the set value, the set level of reactive current is determined:

$$I_{0\text{p}}(n) = I_{0\text{p}n}(n) - I_{0\text{p}KU}(n)$$

   where $I_{0\text{p}KU}$ is the value of the reactive current of the load node when static capacitors batteriesnnstage is turned on

   To determine $I_{0\text{p}KU}(n)$, we introduce the notation:

$$A+\sqrt{A}\cos(\varphi_C-\varphi_0)=B$$

Where, $A=\{I_{0a}^2(n)+I_{0\mathrm{p}KU}^2(n)\}^2(R_0^2+X_0^2)$

$$\varphi=arctg[\left(I_{0\mathrm{p}n}(n)+I_{0\mathrm{p}KU}(n)\right)/I_{0a}(n)]$$

$$B=U_C^2-U_0^2(n)/2U_0(n)$$

The solution of the nonlinear equation $A+\sqrt{A}\cos(\varphi_C-\varphi_0)=B$ relatively $I_{0\mathrm{p}KU}\ (n)$ was carried out using recurrent difference digital modeling methods.

Further, taking into account the calculated $I_{0\mathrm{p}KU}(n)$, the required reactive power of additional compensation in the node to the load is determined at the specified U_0(n):

$$Q_{\mathrm{add.p}}=Q_{0\mathrm{p}}(n)-\sqrt{Z}I_{0\mathrm{p}KU}(n)U_0(n)$$

5. Reactive power (total) of the entire industrial facility Q_{oc}(n) is calculated for U_0 (n):

$$\mathrm{Q}_{0C}(n)=\mathrm{Q}_0(n)+\Delta\mathrm{Q}_0(\mathrm{n})$$

6. Costs for the required reactive power compensation for certain levels U_0 (n) are calculated based on the previously obtained ΣΔP(n) and Q_{oc}(n) according to the formula:

$$Z(n)=C_a\sum\Delta P(n)+C_P Q_{\mathrm{add}}\ (n)$$

where C_a is the price of active power RUB / kV h; C_P - the price of reactive power rub/kvAr h

7. Based on the results obtained, a database is compiled (in tabular or graphical form), by comparing the optimal variant U_0(n) and $\Delta\mathrm{Q}(\mathrm{n})$, with the minimum $E(n)$, is determined.

8. A check is carried out for the fulfillment of the accepted restrictions (loading of synchronous motors and settings of their excitation currents, the discreteness of the static capacitors batteries stages, etc.) when implementing the calculated level of compensation of the reactive power $\Delta\mathrm{Q}_0(\mathrm{n})$ in accordance with the results of the check, a task is issued to calculate the next stage of the static capacitors batteries (either to decrease the reactive power, or to increase) or to stop the calculation.

As it was indicated in clause 6 of the calculation algorithm, the total costs are made up of the cost of the PFC unit and the cost of the uncompensated reactive power.

Thus, according to the results of the calculations, the optimal parameters of the BSC (the number of steps of static capacitors batteries, their unit reactive power, the dead zone) are selected under the conditions of the given load graph of the load node under consideration, for the option with the lowest cost value Z from the uncompensated reactive power.

As an example, Fig. 2 shows a three-dimensional dependence of costs Z (rubles) on the cost of static capacitors batteries (rubles) and the number of its steps i.

Alternatively, this problem was simplified for the above-listed static capacitors batteries connection schemes by constructing graphical dependencies (based on the cost data of equipment catalogs).

Fig. 1-b shows the example of relation between averaged efficiency of PFC unit (6kV, 900 kVAr, circuit of direct connection of multiple section static capacitors battery) use E and the number of control stages m. Fig.1-b also shows averaged relations of energy saving Ee and costs C for reactive power compensation units purchase.

It is obvious that for this variation of connection circuit maximum value of averaged efficiency of unit use corresponds to three steps of control. During research database of price of modern PFC units for 6-10 kV and their main power elements was based on a review of price lists of main manufacturers of reactive PFC units, high-voltage capacitors batteries, electromagnetic contactors, thyristor keys, vacuum switchers.

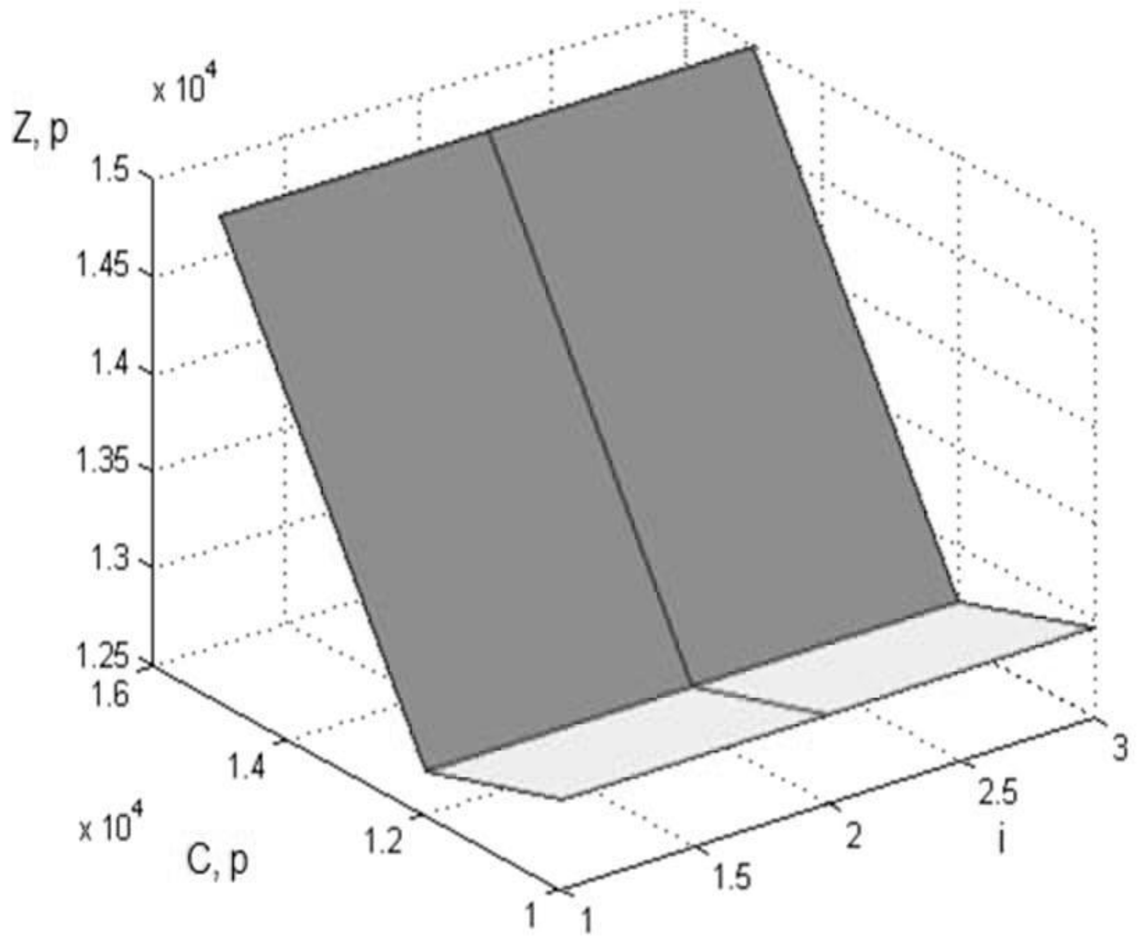


Fig. 2 Three-dimensional dependence of costs Z on the cost of static capacitors batteries and the number of its steps

To determine level of energy saving caused by decrease of reactive power circulation simplified approach was used with equivalent losses factor Kp. The latter shows the level of decrease pf active power losses when compensating inductive reactive power [18].

For 0.4-220 kV power supply systems value of Кп = 0,07-0,15. Taking into account presence of distribution networks of several levels of voltage transformation, value Кп=0.12 was taken average in further calculations.

Average annual energy saving caused by decrease of reactive current circulation that can be compensated by static capacitors battery with Qkb power, was determined by following equation:

$$E = Kp\ Ce\ Qkb\ (1\text{-}1/m)$$

Where Ce – averaged cost of active power (kW/h)
Qkb – total capacity of PFC unit (kVAr)
t – time of reactive power compensation by the unit (h)
m – number of control steps

At the same time, it was taken into account that level of power losses directly related to the accuracy of reactive power regulation determined by number of control steps m.

CONCLUSIONS

This methodolodgical approach for solving engineering problems of paramentric optimization of controlled high voltage capacitors batteries can be used not only for PFC unit of 6-10 kV but for higher voltage 35-220 kV. In this regard it is necessary to consider technological characteristics of the section of electric power industry imposing additional requirements for reliability, power quality and overall energy efficiency [19].

For example, for distributing network from 35 kV and stricter requirements are imposed for voltage tolerances, unsinusoidality than for 6-10 kV power supply systems. Additional accounting of seasonal and daily variations of power consumption, change of weather conditions is required as well as spatial optimization of power consumption modes related to tasks of regional power supply system.

Received February 2021, accepted March 2021)

LITERATURE

[1] Federal Law of November 23, 2009 N 261-ФЗ "On energy saving and on improving energy efficiency and on amending certain legislative acts of the Russian Federation" (with amendments and additions), 2009.

[2] Order of the Ministry of Energy of the Russian Federation dated June 23, 2015 N 380 "On the Procedure for Calculating the Ratio of Active and Reactive Power Consumption for Individual Power Receiving Devices (Groups of Power Receiving Devices) of Electric Power Consumers", 2015.

[3] Karymov, R.R., Lurie, A.I., Safiullin, D.K. (2013). Reactive power compensation device//Patent of the Russian Federation No. 2479907.

[4] Vasiliev, S.N., Goncharenko, V.P., Latmanizov, M.V., Mizintsev, A.V. (2012). Device for automatic regulation of reactive power compensation//Patent of the Russian Federation No. 2459335.

[5] Bryantsev, A.M. (2014). Static reactive power compensator//Patent of the Russian Federation No. 2510556.

[6] Titov, V. G. Compensation of reactive power in the load node of the distributed power supply network using intelligent electric drive tools [Text]/V. G. Titov, A. S. Plekhov, O. V. Fedorov//Industrial energy. - 2012. - No. 5. - S. 51-56.

[7] Bastron, A.V., Davydov, D.A., Kostyuchenko, L.P. (2007). Device KMM//Utility model of the Russian Federation No. 66620.

[8] Krysanov, V.N. (2017). Hardware - software control of load node modes of regional power supply networks using static devices: monograph/Krysanov V.N. Voronezh: FSBOU VSTU, p 234.

[9] Shishkin, S.A. (2005). "Thyristor contactors for switching low-voltage capacitive load," Power electronics, No. 2.

[10] Power Factor Correction. Product Profile. Published by EPCOS AG. Ordering No EPC: 26013-7600. Germany. - 103p. 2005.

[11] Power Factor Correction. Product Profile 2003/2004. Published by EPCOS AG. Ordering No EPC: 26011-7600. Germany. - 87p. 2003.

[12] Reactive Power Controller Prophi. Operating instructions. Janitza electronics GmbH. Dok Nr 1.020.009.a Serie II. Germany. - 56p. 2003.

[13] Gevorkyan, M.V. (2003). Modern components of reactive power compensation (for low-voltage networks). M.: Dodeka XXI, p. 64.

[14] A.S. No. 1576983, E.A. Sepping, I.V. Davydov, Yu.A. Kala, A.P. Reiner and Y.Ya. Yarvik; Tallinn Polytechnic Institute. - 2756468/24-07. Bul. No. 9. 1981.

[15] A.S. SU No. 1112485 A, N.I. Dzhus, V.V. Krasnik and G.V. Krasnik; All-Union Institute for Advanced Training of Management Workers and Light Industry Specialists. - 3550412/24-07. Bul. No. 33. 1981.

[16] A.S. No. 767896 A.A. Yatsenko, Yu.N. Burmanty; Three-phase shunt capacitor unit. - 2691623/24-07. Bul. No. 36. 1981.

[17] Certificate of state registration of the computer program. Determination of optimal parameters of a capacitor plant for reactive power compensation according to the minimum cost criterion [Text] / V. N. Krysanov, V. L. Burkovsky, K. V. Ivanov (Russia). Application no. 2017618141 Application no. 2017615096. 2017.

[18] Zhelezko, Yu.S., Artemyev, A.V., Savchenko O.V. (2006). Calculation, analysis and rationing of electric power losses in electrical networks: Manual for practical calculations. M.: Publishing House NC ENAS, 286 s.

[19] Babenko, V. V. (2020. Features of reactive power compensation in electric power networks and systems / V. V. Babenko, I. A. Khaychenko, Yu. V. Nefedov. (2020)./ / National Association of Scientists. Problems of technical sciences; №57(1): 48-52 c.