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doi:10.15199/48.2015.11.22

Compensation of reactive power in electrical supply systems of large industrial enterprises

Abstract. *The issues of reactive power compensation, typical for large industrial enterprises are discussed in the article. The approach to reactive power compensation is considered as an optimization problem. On the one hand, this approach allows minimizing the costs of compensating devices; on the other hand, it allows economically justifying the amount of cost for the "consumption" of reactive power born by the enterprise. The practical solution of the formulated problem in the existing large metallurgical plant in Mariupol (Ukraine) is presented.*

Streszczenie. *W artykule omówiono zagadnienia kompensacji mocy biernej, typowe dla dużych przedsiębiorstw przemysłowych. Zagadnienia kompensacji mocy biernej potraktowano jako problem optymalizacji. Z jednej strony pozwala to na minimalizację kosztów urządzeń kompensacyjnych; a z drugiej na ekonomiczne uzasadnienie wysokości kosztów za „pobór" mocy biernej przez przedsiębiorstwo. Zaprezentowano praktyczne rozwiązanie sformułowanego problemu w istniejącym dużym zakładzie metalurgicznym w Mariupolu (Ukraina).* ***(Kompensacja mocy biernej w systemach zasilających duże zakłady przemysłowe).***

Keywords: reactive power, reactive power compensation, payment for reactive energy.
Słowa kluczowe: moc bierna, kompensacja mocy biernej, opłaty za energię bierną.

Introduction

At the present time an increase of reactive power (RP) "consumption" in all areas of industry and national economy is observed. Users of electric energy began to operate with low power factor and thus the increase of reactive power consumption has led to a number of negative consequences. Experts estimate that among the reasons of emergence and development of the most serious damages and technological breakdowns in power supply systems in different countries, that have led to disconnection of a significant amount of consumers, was the deficit of RP in power supply systems and the insufficient power of installed RP sources [1].

Therefore the issues of reactive power compensation (RPC) are the aspects of both energy saving in electrical networks and reliability of electrical power supply of industrial enterprises. Rational use of compensating devices (CD) helps to reduce power losses in electrical network and to provide appropriate quality of consumed electrical energy due to the normalization of voltage levels, thus generally allowing achieving high technical and economic performance indices of electric installations.

In that context the interest in the issues of RPC has considerably increased in Ukraine in the recent years. Elimination of reactive power flows in the networks can provide the annual savings of about 150 million kWh of electrical energy [2,3,4,5].

Legal system of Ukraine in the field of payment for the consumed reactive energy

According to the Law of Ukraine "On Electric Power Industry" (revised on 26.04.2015 with amendments and additions introduced by the laws of Ukraine): "The energy consumer must follow the requirements of normative technical documents and contracts on the supply of energy". Normative technical document in the field of payment for the consumed reactive energy is "Method of payment calculation for reactive power flows between the electric power supply organization and its consumers" [6].

According to the mentioned method payment for consumption and generation of reactive power is determined by three components [6]:

(1) $$R_{\Sigma} = R_1 + R_2 - R_3 ,$$

where: R_1 – the basic payment for consumption and generation of reactive power; R_2 – supplement for insufficient RPC equipment installed in consumer electrical network; R_3 – the discount in case of consumer participation in optimal daily regulation of network regimes performed by power supply organization for the accounting period.

The basic payment for consumed and generated reactive energy is defined by the following formula:

(2) $$R_1 = \sum_{i=1}^{v} \left(WQ_{cons.i} + k \cdot WQ_{gener.i} \right) \cdot D \cdot T_i ,$$

where: v – number of reactive energy accounting points; $WQ_{cons.i}$ – "consumption" of reactive power at the accounting point for the period of settling, kvarh; $WQ_{gener.i}$ – generation of reactive power to the power supply organization network at the accounting point for the period of settling, kvarh; $k = 3$ – a normative coefficient of power system losses caused by reactive energy generated by the consumer network; D – economic equivalent of reactive power (EERP) that characterizes the share of influence of reactive power flow at the accounting point on technical and economic indices in accounting regime, kW/kvar; T_i – actual average purchase price of electrical energy for the period of settling (calculated in accordance with the normative documents of National Energy Regulation Commission (NERC) of Ukraine), UAH/kWh.

The calculation of EERP is performed by power supply organization every two years. Value of EERP and coefficient of losses caused by generation of RP by consumer network is specified in the Agreement.

The basic payment for consumed and generated reactive energy when zonal energy accounting is used, is the result of the summation of components R_1, defined for each zone of daily electrical load similar to expression (2). In this case, the payment for RP generation is calculated only for the zone of minimum daily electrical load taking the actual average purchase price.

Supplement for inefficient RPC equipment installed in consumer electrical network is defined by the formula:

(3) $$R_2 = R_1 \cdot C_{bas} \cdot (k_f - 1),$$

where: $C_{bas} = 1$ – normative basic value of coefficient of capital investments stimulating to RPC resources in electrical networks of consumer; k_f – a coefficient which is selected from [6] (Table 1) depending on the actual average power factor of consumer $tg\varphi$ for the period of settling.

Neutral zone of supplement R_2 in respect to "consumption" of reactive power, limited to value of the maximum power factor – $\cos\varphi_g$ = 0,97 ($tg\varphi_g$ = 0,25) is introduced in [6] (Table 1). The supplement is applied if the actual power factor is less than the adjusted value $\cos\varphi_g$.

The average actual power factor of consumer network for the accounting period is defined by the formula:

(4) $$tg\varphi = \frac{WQ_{cons}}{WP},$$

where: WP – active power consumption in the period of settling, kWh; WQ_{cons} – reactive energy consumption in the same period, kvarh.

In the case of value of $tg\varphi$ bigger than 2,00, for the selection of k_f the value $tg\varphi = 2{,}00$ is taken.

Discount in payment for consumption and generation of reactive power R_3 is possible when there is sufficient RPC equipment installed in the consumer electrical network, zonal calculation of consumed and generated electrical energy is available, consumer performance of daily consumption and generation of electrical energy is determined by electric supply organization and its operational control is possible. Curves of consumption and generation, as well as the height of discount are settled in the Agreement.

If consumer of energy is not involved in the optimal daily regulation of consumption and generation regimes of reactive energy, the discount R_3 is not available.

Optimization of the power of RPC devices

Installation of various types and power RPC resources leads to different effects. Among the variety of RPC options only one is optimal. Assuming that reactive power load of consumer equals to value Q_L and optimal power of CD obtained from the calculation equals to $Q_{CD\,opt}$, then the optimal value of reactive power consumed from power system network is defined by the difference:

(5) $$Q_{PS\,opt} = Q_L - Q_{CD\,opt}.$$

The objective of optimization calculation can be both determination of $Q_{CD\,opt}$ and $Q_{PS\,opt}$. The second version is usually easier.

Below the problem of determination of optimal value of reactive power consumed from power system network is considered, based on the minimization of mentioned annual costs associated with the purchase, transmission and compensation of reactive power. In this case, the following condition must be satisfied:

(6) $$C = C_{TR} + C_{CD} + C_R \to \min,$$

where: C_{TR} – cost of RP transmission; C_{CD} – cost of CD; C_R – payment for reactive energy.

Costs of RP transmission are associated with the additional losses in the elements of electrical network and are defined by the expression:

(7) $$C_{TR} = \frac{Q^2}{U^2} \cdot R \cdot \tau \cdot b,$$

where: Q – reactive power consumed by load; U – nominal voltage of network at the installation point of CD; R – ~~is~~ equivalent resistance of network; τ – the usage time of power losses; b – average cost of power losses (average tariff rate on active power).

The usage time of power losses is defined by the expression:

(8) $$\tau = \left(0{,}124 + \frac{T_M}{10^4}\right) \cdot 8760,$$

where: T_M – the amount of hours of maximum load usage.

The costs of CD C_{CD} will depend on the type of compensating devices used. In the case of installation of banks of capacitors (BC) as CD, their cost can be calculated as follows:

(9) $$C_{CD} = C_{BC} = (E_n + E_d)(C_{0.BC} + C_{1.BC} Q_{BC}) = \\ = (E_n + E_d)(C_{0.BC} + C_{1.BC}(Q_L - Q)),$$

where: E_n, E_d – accordingly normative efficiency coefficient and depreciation; $C_{0.BC}$ – permanent costs of BC installation; $C_{1.BC}$ – specific costs of 1 kvar of power generated by BC; Q_{BC} – RP generated by BC.

In case of using synchronous motors (SM) operating in the regime of overexcitation as CD, their cost can be calculated as follows:

(10) $$C_{CD} = C_{SM} = C_0 + C_1 \cdot Q_{SM} + C_2 \cdot Q_{SM}^2,$$

where: C_0 – constant component of costs independent from generated RP and taking into account the cost of regulator; C_1 – specific costs on 1 kvar of power generated by SM, dependent on the cost of losses and constant values for the given motor and its parameters; C_2 – specific costs proportional to the square of generated RP, Q_{SM} is RP generated by SM.

The payment for reactive energy in case $R_3 = 0$ will be defined by the expression:

(11) $$C_R = R_1 + R_2 = Q \cdot T_M \cdot D \cdot b \cdot k_f.$$

The coefficient k_f can be approximated by the expression:

(12) $$k_f = 1 + (tg\phi - 0{,}25)^2 \approx 1 - 0{,}41 \cdot tg\phi + 0{,}97 \cdot tg^2\phi = \\ = 1 - 0{,}41 \cdot \frac{Q}{P_L} + 0{,}97 \cdot \left(\frac{Q}{P_L}\right)^2,$$

where: P_L – active load of consumer.

The optimal value of RP consumed from power system Q_{PS} can be found from the equation:

(13) $$\frac{dC(Q)}{dQ}=\frac{dC_{TR}(Q)}{dQ}+\frac{dC_{CD}(Q)}{dQ}+\frac{dC_R}{dQ}=0\,.$$

Figure 1 illustrates the dependence of the costs on the consumed RP using BC as compensating devices.

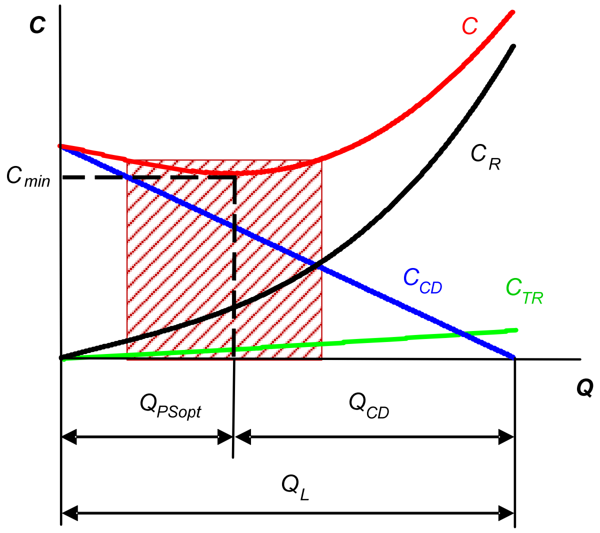

Fig.1. Dependence of the costs of transmission of RP, CD installation and rate for reactive electrical energy

Researchers have shown that for the majority of large electrical energy customers, the total costs function corresponding to the optimal level of compensation with use of BC as compensating devices, at a certain interval varies only slightly (the shaded area on figure 1). In this case, the selection of the level of compensation in this interval can be made considering not economic, but technical conditions, for example aiming at voltage regulation in electrical power system.

Therefore, the use of BC as a means of RPC in large industrial enterprises has a number of advantages: small specific losses of active power, lack of moving parts, easiness of installation and operation, relatively low cost, light mass, lack of noise during operation, ability to be installed near separate power consumers.

The main advantage of using SM for RPC compared to BC is the possibility of modulated regulation of generated reactive power. However, active losses related to generation of RP in synchronous motors are considerably higher compared to losses in BC, as they depend on the square of the generated power of SM. Additionally, when using SM for RPC, the function of total costs includes salient minimum. This makes it difficult to solve the problems of optimal RPC and nodal voltage regulation in the electrical network simultaneously. In this regard, SM is used mainly for RPC on load-peak in power supply systems of industrial enterprises.

The practical solution of RPC in large industrial enterprise

Below the practical solution of RP regimes optimization has been considered on the example of large industrial enterprise located in Mariupol'. Figure 2 shows a simplified single-line schematic diagram of power supply network of the company, where the authors carried out the research.

In the considered diagram the BC and SM are sources of RP. Additionally, CHP turbine generators, which can also be used for RPC, are connected to bus of substation SS-3.

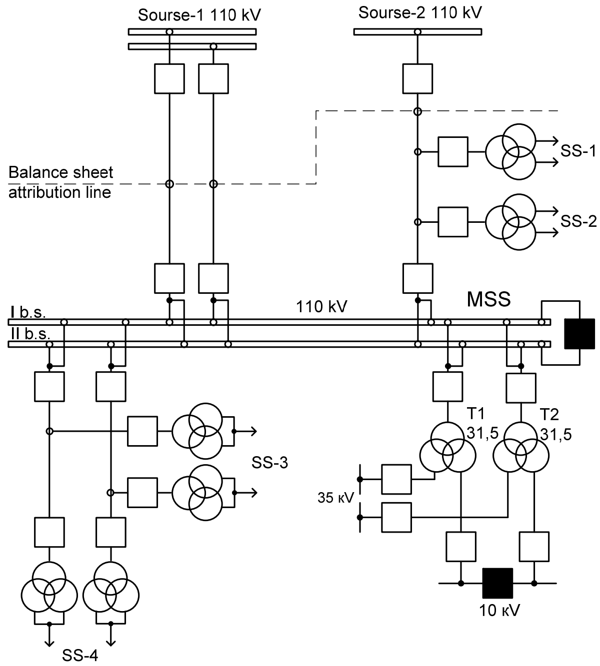

Fig.2. A simplified single-line schematic diagram of power supply network of a large industrial enterprise

At the time of research it was observed that RPC, which was carried out in part by generation of RP by synchronous motors and partly due to the use of BC, was inefficient. At the same time under-utilization of more than 60% of installed power of BC was found. Total losses of active electrical energy caused by reactive power flow amounted to approximately 500 MWh, or about 9% of the total losses of active electric power. For example, figure 3 and figure 4 show daily values of power factor $tg\varphi$ measured in the transformers T1 and T2 of main step down substation (MSS) in the research period.

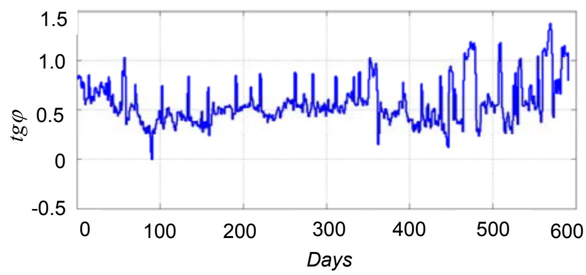

Fig.3. Daily average $tg\varphi$ of transformer load T1 MSS

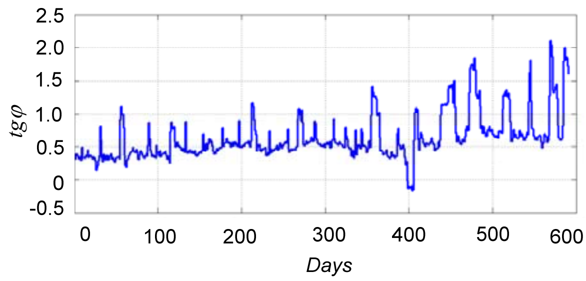

Fig.4. Daily average $tg\varphi$ of transformer load T2 MSS

Figure 3 and figure 4 show that daily average power factor $tg\varphi$ in most cases exceeds limit value $tg\varphi_g$ = 0,25, which results in an increase of payment for reactive electrical energy.

Several measures to optimize RPC were considered: the full use of all installed power of BC, the use of turbine generators HPS, purchase and installation of additional regulated BC. It should be noted that full use of the available reactive power of SM was not considered. This variant had to be abandoned due to overheating of SM, when operated in the regime of maximum possible generation of RP, which was observed in practice.

In the first variant it was proposed to use the available power reserve of BC without additional capital expenditures for the purchase of new equipment. As a result of calculations it was found that a profit achieved by reducing losses and payments for RP would be about 1 million UAH per year with reduction of the value of RP consumption by 17%. In the second variant it was proposed to use the existing BC and turbine generators HPS for RPC. In this case, the profit achieved by reducing losses and the payment for RP was more than 1,6 million UAH per year, with reduction of the value of RP consumption by 33%. The third variant suggested using the existing BC, turbine generators HPS and additional installed adjustable BC. In this case, because of more flexible RPC, the profit achieved by reducing losses and the payment for RP was more than 4,7 million UAH per year, with reduction of the value of RP consumption reduction by 80%.

In all variants, because of using BC for RPC, a posibility of resonant modes at frequencies of higher harmonics had to be taken into consideration, as valve inverters are components of loads. It was considered that the limits of RP regulation by turbo generators of old series were severely tightened. This limitation is related to the increased heating, increase of mechanical stress in stator core ends, as well as the requirements to ensure the stability conditions [7].

Researchers have shown how difficult is to find the optimal RPC solution in existing large industrial enterprise. It is almost impossible to focus on only single variant of RPC. The development of a series of recommendations on RP regimes optimization depending on specific conditions is needed.

Conclusion

In the large industrial enterprises almost all known sources of RP can be used. To ensure the optimal balance of RP in power system of enterprise, the proper management of power consumption fulfilling requirements of the electricity market is needed.

Using BC as RPC devices requires an essential integrated study of electrical energy quality indices and frequency characteristics considering the entire diagram of power supply of the enterprise.

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