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Analysis of the of reactive power compensation possibilities in a mining plant – case study

Analiza możliwości kompensacji mocy biernej w zakładzie górniczym – studium przypadku

Abstract. *This article presents a method for analysis during the selection process of reactive power compensators in the power grid of a mining plant. The selection was made based on the measurements values of the average 15-minute loads of one of the transformers that supplied the underground mine. The possibility of using capacitor banks and underloaded large-power synchronous motors of fan drives was considered. Measurements taken before and after the implementation of the automatic reactive power compensation system are presented.*

Streszczenie. *W artykule przedstawiono analizę doboru kompensatorów mocy biernej w sieci elektroenergetycznej zakładu górniczego. Doboru dokonano na podstawie pomiarów średnich 15-minutowych obciążenia jednego z transformatorów zasilających zakład. Rozpatrzono możliwość wykorzystania baterii kondensatorów oraz niedociążonych silników synchronicznych dużej mocy napędu wentylatorów. Zaprezentowano pomiary wykonane przed wdrożeniem i po wdrożeniu systemu automatycznej kompensacji mocy biernej.*

Keywords: reactive power compensation, automatic control, synchronous motor
Słowa kluczowe: kompensacja mocy biernej, automatyczna regulacja, silnik synchroniczny

Introduction

Reactive power compensation is carried out to relieve the grid of the flow of reactive currents, which is achieved by eliminating the phase shift between the fundamental harmonics of current and voltage and eliminating the load current harmonics regardless of the shape of the supply voltage. Under such conditions, the source current and apparent power are minimised for a specific active power of the load [1-3]. There are many known methods of reactive power compensation, both fundamental and distortion power (with elimination or significant reduction of harmonics), and also enabling voltage stabilisation at selected points in the grid [2, 4-18].

In an industrial power grid, partial compensation is usually used, which involves compensation of the fundamental harmonic of the current and voltage in order to maintain the power factor within acceptable range, and thus to limit active power losses and voltage drops in the supply lines. The current harmonics of the loads are limited by the passive harmonic filters. The other solutions to limit the current harmonic are compensation systems based on active filters, usually cooperating with a selected set of passive filters, which are also increasingly implemented [4, 10, 19-21].

In addition to the technical aspects of reactive power compensation, economic aspects are also important [3, 8, 22-24]. In addition to the costs associated with power transmission in the grid, failure to meet the appropriate parameters of power consumed by consumer at the PCC (Point of Common Coupling) results in additional fees charged by the DSO (Distribution System Operator).

The largest consumers of electricity are the heavy industry. Mining plants are one of them. Electricity costs are one of the significant components that determine the profitability of production. For this reason, any effort to reduce energy costs is highly desirable.

The process of modernising existing systems is usually a compromise between engineers' proposals for the modern (and usually the most expensive) technical solutions and investment costs. Industrial practice shows that the simplest solutions are often implemented to minimise costs and achieve the intended effects. For this reason, traditional reactive power compensation methods should not be abandoned.

To reduce the costs of electricity, it is necessary to appropriately compensate the reactive power drawn from the power grid at each PCC. The proper selection of compensation devices requires an analysis of the load variations in the plant.

Case study

The object of the analysis was one of the mining plants in Poland. Measurements were taken at the 110/6 kV switchgear that supplies the mine. The power supply is realised by 40 MVA main transformers to the separate bus sections. The considerations of this paper are limited to the analysis of one main power transformer.

Table 1 shows the active and reactive energy recorded during the measurement period in one of the main transformers in the PCC and the average value of the power factor $tg\varphi$ determined based on energy consumption.

Table 1. Active and reactive energy and the average power factor $tg\varphi$ during the measurements time at the PCC.

Day of a week	Active energy	Reactive energy	Average power factor
	E_P [MWh]	E_Q [MVArh]	$tg\varphi_{AVG}$ [-]
Monday	467.3	245.9	0.526
Tuesday	504.5	249.4	0.494
Wednesday	462.9	237.7	0.514
Thursday	453.6	255.3	0.563
Friday	460.7	253.5	0.550
Saturday	495.1	316.5	0.639
Sunday	307.3	192.2	0.625
Total	**3151.4**	**1750.5**	**0.555**

During the measurements, the 15-minute average values of the active and reactive power of the power transformer at the PCC were recorded. The recorded waveforms are characterised by a high repeatability of the loads on individual working and non-working days. For further analysis, the day with the highest and the day with the lowest active energy consumption was chosen.

Fig.1 shows the 15-minute average values of active and reactive power for one working day (Tuesday) and one non-working day (Sunday) and the power factor $tg\varphi$ defined as

(1) $$tg\varphi = \frac{Q}{P},$$

where: P – fundamental active power, Q – fundamental reactive power.

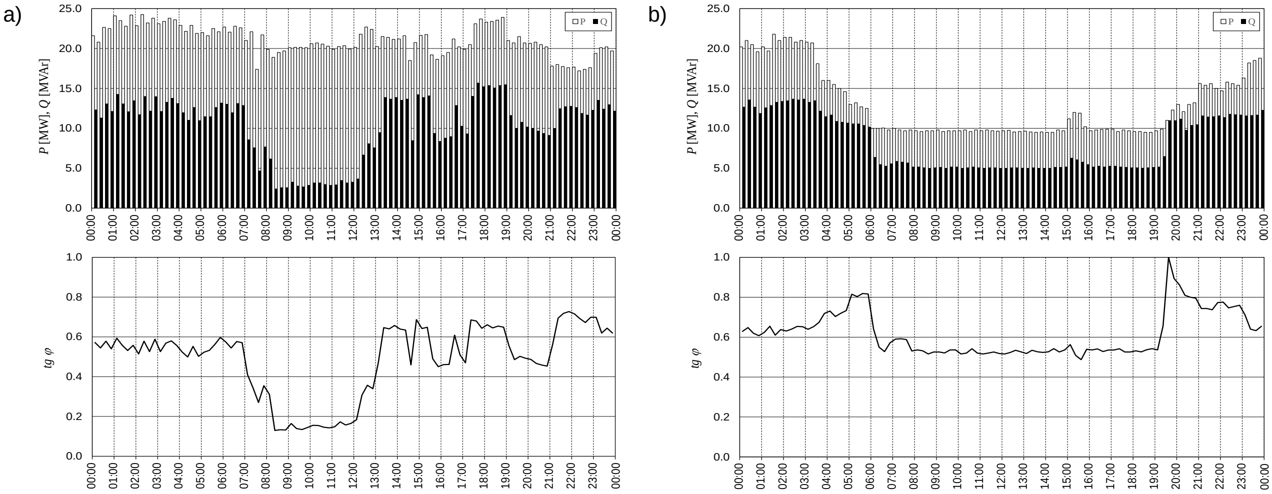


Fig. 1. The 15-minute average values of active and reactive power and the power factor $tg\varphi$ at the PCC: a) working day, b) non-working day

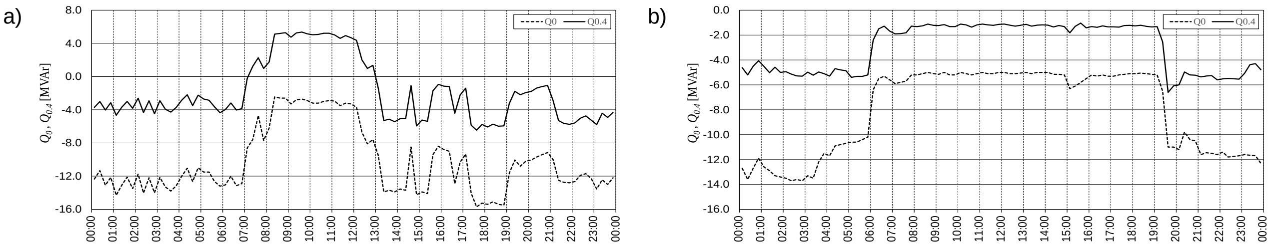


Fig. 2. Minimum and maximum reactive power of the compensator to maintain the power factor $tg\varphi$ at the PCC within the acceptable range: a) working day, b) non-working day

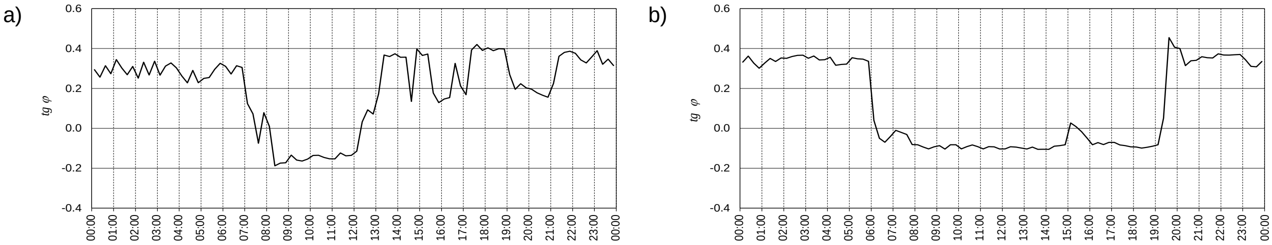


Fig. 3. Estimated power factor $tg\varphi$ after permanently connecting an additional compensator with a power of 6 MVAr at the PCC: a) working day, b) non-working day

A positive sign for inductive reactive power and a negative sign for capacitive reactive power were assumed.

Analysis of reactive power demand

The reactive power demand of additional compensation devices can be determined on the basis of the following [20, 24, 25]:

- active and reactive power values drawn by the loads from the PCC under consideration,
- actual value of reactive power consumed by loads,
- acceptable range of power factor changes resulting from the contract with the DSO.

In the analysed case, the required power factor $tg\varphi$ at the plant PCC should be in the range 0-0.4.

As can be seen in Fig.1, on a non-working day the power factor exceeds the permissible value of 0.4, and on a working day it only periodically drops below this value.

In order to ensure that the power factor at the plant PCC is maintained within the permissible range

(2) $$0 \le tg\varphi \le tg\varphi_{\max}$$

the minimum value of the capacitive reactive power of additional compensators should be equal to the difference between the power currently drawn from the grid and the power for which the power factor reaches the upper permissible limit

(3) $$Q_c = Q - P \cdot tg\varphi_{\max} \; .$$

Fig.2 shows the minimum and maximum reactive power of additional compensators necessary to maintain the power factor $tg\varphi$ at the plant PCC in the range of 0-0.4 on a working and a non-working day.

Based on the values in Fig.2, it can be assumed that the required reactive power of additional compensators should be approximately 6 MVAr. Fig.3 shows the expected power factor $tg\varphi$ after permanently connecting an additional compensator with a power of 6 MVAr.

As can be seen in Fig.3, static turn-on of the 6 MVAr compensator will cause overcompensation in certain time intervals both on a working and on a non-working day. To avoid such a case, the compensator can be switched off. However, this will increase the power factor $tg\varphi$ above the acceptable value during this time.

The solution in such a case is to use a compensator with adjustable reactive power, e.g. sectioned capacitor banks [3, 20, 24, 25].

Based on the measurements carried out, it was proposed that 1.2 MVAr and 4.8 MVAr capacitor banks with independent control would be used. Fig.4 shows the power of the switched capacitor banks and the expected power factor $tg\varphi$ at the PCC.

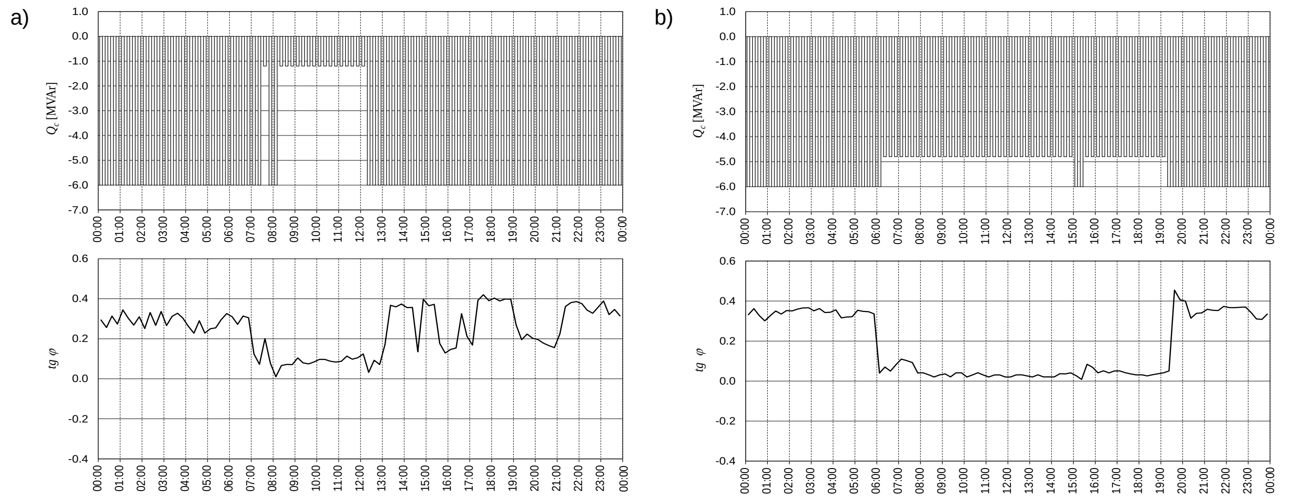


Fig. 4. Estimated reactive power of the sectioned capacitor bank and the estimated power factor $tg\varphi$ at the PCC: a) working day, b) non-working day

In the case of powering loads generating significant current harmonics, like e.g. thyristor hoisting machines, capacitor banks should be protected by detuning chokes. In such cases, passive harmonic filters are also installed, which are an additional source of capacitive reactive power, and increasingly often also active filters that enable the stepless regulation of their reactive power [4, 10, 19, 21].

Synchronous motor as a reactive power compensator

The specificity of underground mining plants is the continuous operation of many drives with synchronous motors, regardless of the mine's production cycle. This group mainly includes compressors and underground mine ventilation fans, which usually operate with a load lower than the rated.

The reactive power of such a motor in the synchronous operation state can be regulated by changing the field current [5-7, 9, 10, 17, 26, 27]. The field current should be controlled in a way that ensures stable operation of the drive, without the risk of the motor falling out of synchronism.

The considered main transformer supplies power to the three salient-pole synchronous motors of GAe1716t/01 type with the rated data shown in Table 2. The motors are located in the ventilation fan station, of which 2 are always in operation, and the third is a reserve. These motors typically operate with an active power load of 2200 kW.

Based on the known relationships for the synchronous operation of a salient-pole motor, a number of characteristics can be derived to determine the possible changes in the field current and the range of the motor's reactive power control.

Table 2. Rated data of the GAe1716t/01 synchronous motor

Parameter	Symbol	Value
Mechanical power	P_{mN}	3150 kW
Electrical power	P_N	3274 kW
Stator voltage	$U_{N(Y)}$	6000 V
Stator current	I_N	350 A
Field voltage	U_{fN}	90 V
Field current	I_{fN}	313 A
Frequency	f_N	50 Hz
Rotor speed	n_N	375 rpm
Power factor	$cos\varphi_N$	0.9 cap.
d-axis synchronous reactance	X_d	11.38 Ω
q-axis synchronous reactance	X_q	7.82 Ω
Stator winding resistance (75°C)	R	0.088 Ω
Field winding resistance (75°C)	R_f	0.282 Ω

The limitations of the reactive power control range result from the rated values of the stator and field current and the permissible power angle. Motors manufacturers do not recommend the operation of the machine at a power angle greater than the rated one. For the considered motors, the rated value of the power angle was determined as θ_N=22.9°.

Fig.5 shows the selected characteristics derived for the GAe-1716t motor. The rated power load, the load under typically operating conditions and the load at idle operation were considered.

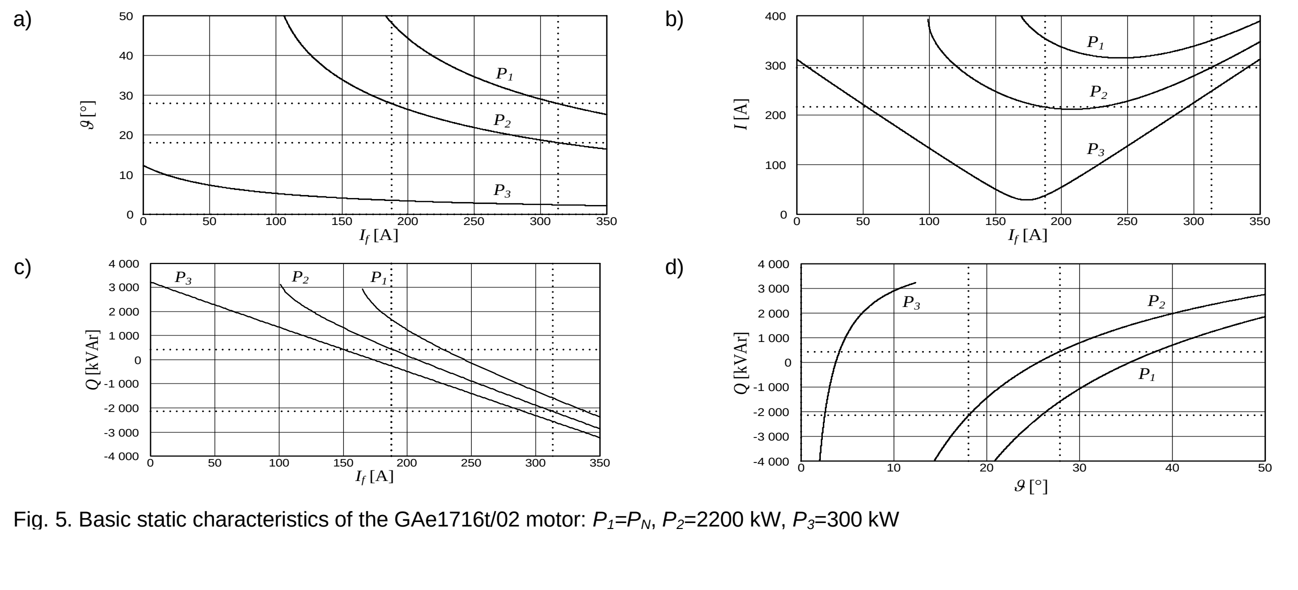


Fig. 5. Basic static characteristics of the GAe1716t/02 motor: P_1=P_N, P_2=2200 kW, P_3=300 kW

Based on these characteristics, assuming a 6 kV supply voltage, the reactive power regulation range of a single motor with the 2200 kW load was determined.

The minimum permissible value of the field current is determined based on Fig.5a) for the rated power angle.

From Fig.5c) at the minimum permissible field current value of 188 A, it is possible to achieve the inductive reactive power of 434 kVAr and at the rated field current - the capacitive reactive power of 2144 kVAr.

As follows from Fig.5.b) that in the assumed range of field current changes, the stator current will not exceed the rated value.

In real operating conditions, supply voltage fluctuations and load changes may occur, which affects the change in power angle. Stable motor operation in synchronism state should be ensured by a local motor reactive power controller [26].

Under the assumed conditions, the reactive power control range with two operating motors is 5156 kVAr. This range of reactive power control of the motors makes it possible to eliminate, under appropriate conditions, the need to switch the sections of the capacitor banks.

Automatic reactive power compensation system

Industrial practice shows that in the case of significant dynamic load changes, attempts to regulate the reactive power by the actions performed by the operators do not result in the desired effects. To automate the reactive power compensation process, a centralised automatic reactive power control system was developed, which allows independent compensation of each PCC of the plant [28].

Based on measurements of instantaneous values of active and reactive power in 110/6 kV main power transformers, the control algorithm determines the capacitor banks to be switched on or off and the reactive power of synchronous fan drive motors.

The system controller also monitors the status of switchgears switches in the plant's power grid and determines the compensators supplied from each power transformer. This eliminates the need for any operator intervention in the event of plant's power grid configuration changes.

The use of synchronous motors as stepless controlled reactive power sources allows compensation of the power resulting from the power steps of the capacitor banks, and with an appropriate control algorithm, it allows limiting the number of capacitor banks switching operations.

Results of the system operation

In the analysed mining plant, an automatic reactive power compensation system was implemented [28]. During the investment process, it was decided to divide the proposed 4.8 MVAr capacitor bank into two sections with capacities of 2.4 MVAr each. The proposed 1.2 MVAr capacitor bank and an additional 0.6 MVAr bank were also installed. The capacitor banks were installed on the main switchboard powered directly from the main power transformer. Three GAe1716t type synchronous motors for mine underground ventilation fans with reactive power controllers [26] were also used.

The instantaneous set value of the power factor $tg\varphi$ at the PCC was 0.2.

Fig.6 shows the waveforms of the average 15-minute values of active and reactive power and power factor $tg\varphi$ at the plant PCC with an active automatic compensation system on a working day (Tuesday) and a non-working day (Sunday). As can be seen, the power factor at the plant PCC was kept within an acceptable range, and most time of the non-working day remained close to 0.2.

Table 3 shows the active and reactive energies and the average power factor $tg\varphi$ over a week with the automatic reactive power compensation system active.

Table 3. Active and reactive energy and average value of the power factor $tg\varphi$ at the PCC with the automatic reactive power compensation system active.

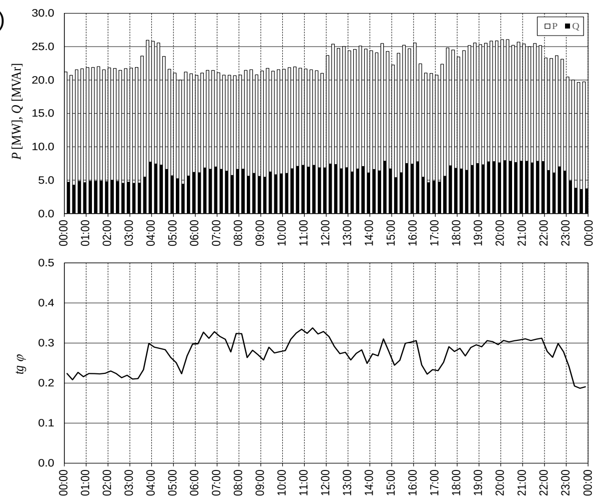
Day of a week	Active energy	Reactive energy	Average power factor
	E_P [MWh]	E_Q [MVArh]	$tg\varphi_{AVG}$ [-]
Monday	506.9	132.8	0.262
Tuesday	549.1	151.1	0.275
Wednesday	510.9	141.7	0.277
Thursday	537.4	139.6	0.260
Friday	485.3	121.9	0.251
Saturday	497.9	128.8	0.259
Sunday	290.7	62.7	0.216
Total	**3378.2**	**878.6**	**0.260**

Summary and conclusions

The paper presents the process of determining the compensators for an automatic reactive power compensation system. The possibility of using sectioned capacitor banks and using fan's underloaded synchronous drives continuously operating motors was taken into account.

Automatic reactive power compensation is particularly important in mining plants, not only due to dynamic load changes, but also due to changes in the parameters of the

a)



b)

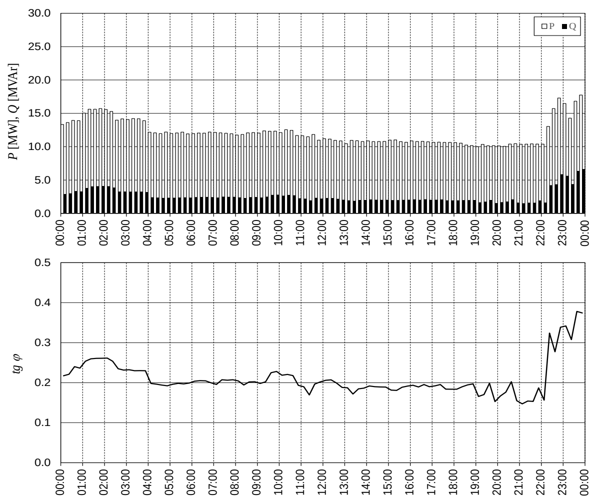


Fig. 6. Waveforms of 15-minute average values $tg\varphi$ of active and reactive power and power factor $tg\varphi$ at the PCC with automatic reactive power compensation system: a) working day, b) non-working day

power grid due to the progress of work in the excavations or the organisation of work.

Properly selected compensators parameters and an appropriate control algorithm taking into account the possibility of stepless regulation of reactive power by underloaded synchronous motors allow maintaining the parameters required by the DSO at the PCC and avoiding additional fees for exceeding them.

From the point of view of investment costs, equipping continuously operating synchronous motors with reactive power controllers and installing power capacitors is the reasonable, low-cost solution for reactive power compensation that, thanks to the appropriate control algorithm, allows the intended effects to be achieved.

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