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Reduction of Electricity Costs and Investment Expenditures in the Power Supply System of a Lubin Mine

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Introduction

Maintaining the copper production at the desired level requires construction of new production sections in more and more distant regions of the reserve. Supplying electric power to production areas at a distance of ten or more kilometers from the shaft, assuring at the same time an adequate power quality (mainly in terms of the voltage magnitude) poses a major problem. Possible measures to at least partly remedy the situation are limitation of starting currents by means of soft-start systems, as well as construction of new feeders. Their effectiveness is, however, limited by technical and economical conditions. Another mean is reactive power compensation.

Power supply system of the Lubin Mine

Fig. 1 View of the Lubin Maine (part of KGHM Polska Miedz)

The main switchboards in Lubin Mine (Fig. 2) are supplied from 6 kV network whose power source are three transformer stations 110/6kV: KLG, KLZ and KLW. In the KLG transformer station contains three transformers rated 31.5 MVA each, and each station KLZ and KLW contains two transformers rated at 16 MVA. At the KLG station the 6 kV network is additionally supplied from two CHP generators with rated power 12.5 MVA each and the third one rated 8.375 MVA. Metering points are located in transformer fields at 110 kV side of KLG, KLZ and KLW stations and in 6 kV fields of power interchange with the heat and power generating plant.

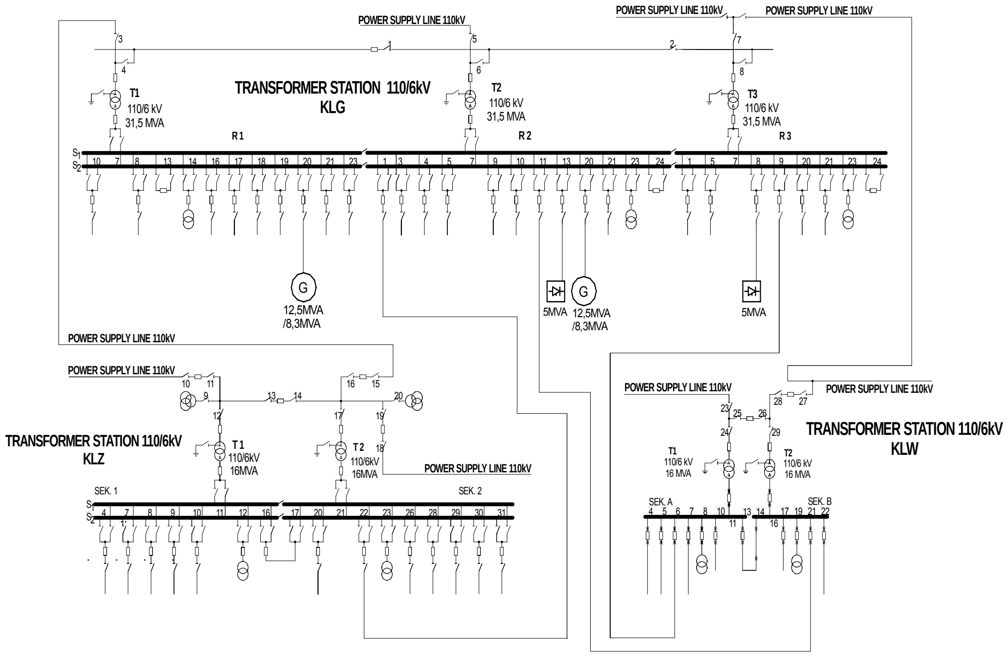

Fig. 2 General diagram of the Lubin Mine power supply network

Electric loads in mining industry are typically 500V induction motors that, apart of the consumed active power, draw also lagging reactive power of about 30% their rated power. According to the data at the end of 2007 an average daily consumption of O/ZG Lubin is ca. 46 MW. Underground loads draw from the 6kV network reactive power within the range of 11÷12 MVAr. Actual tgj in the mine system with synchronous motors running is 0.65, whereas the value specified in the agreement with distribution company is 0.43. Therefore, a reactive power of about 10 MVAr has to be compensated in order to avoid considerable costs, resulting from contractual fines paid on the benefit of the power supplier.

Moreover, the loads operated at low power factor increase feeder currents compared to operation at the same active power with near-unity power factor. A low power factor brings several unwanted effects, including:

- Lower transfer capability of supply networks
- Necessity for the use of cables with larger cross-sectional area
- Increased active power losses in transformers, networks and final circuits
- Increased voltage drops in transformers and feeders.

Reactive power compensation

Historical background

According to the initial assumptions, the basic source of 4MVAr reactive power were to be the CHP plant generators. The remaining part of reactive power in the amount of 8 MVAr should be supplied by synchronous motors of the mine surface drives of rotary converters, main ventilation fans and stationary compressors. However, due to a considerable reduction in heat demand, the CHP plant supplied only 1.0-1.5MVAr of reactive power. An additional limitation of reactive power compensation capability was decommissioning of air compressors for the production sections needs because of the resignation from pneumatic drives and liquidation of energy-consuming compressed air operated equipment; in consequence a part of synchronous motors was turned off from operation. Moreover, the generation of reactive power in synchronous motors is limited by their load. It also increases active power consumption, which for mine fan motors is ca. 30kW/lMVAr and for ball mill drive motors in the ore processing plant is 60-80 kW/1MVAr (relative active power losses associated with reactive power generation depend on the motor design). Analysis of these relations has lead to application of capacitor banks, installed mostly in underground networks, as the main source of capacitive reactive power.

The primary objective, stimulating the implementation of reactive power compensation in the Lubin mine underground network, was the necessity for improving the quality of 6 kV power supply of the production unit situated in the east part of the reserve, about 10 km from the supply sources. Its supply diagram is shown in figure 3. For this purpose a pilot three-section capacitor bank was installed in the Rd-1.1 switchboard and connected to 6 kV network. Power supply parameters were measured at constant load and various power values of the capacitor bank. The results — shown in figure 4, explicitly confirmed the applied compensation method is appropriate. As seen from figure 4, connection of the 1800 kVAr capacitor bank resulted in a 3.63% increase in voltage magnitude at the Rd-1.1 switchboard busbars and 3.06% reduction in transmission losses, in the cable line Rd-19.2 —Rd-1.l only.

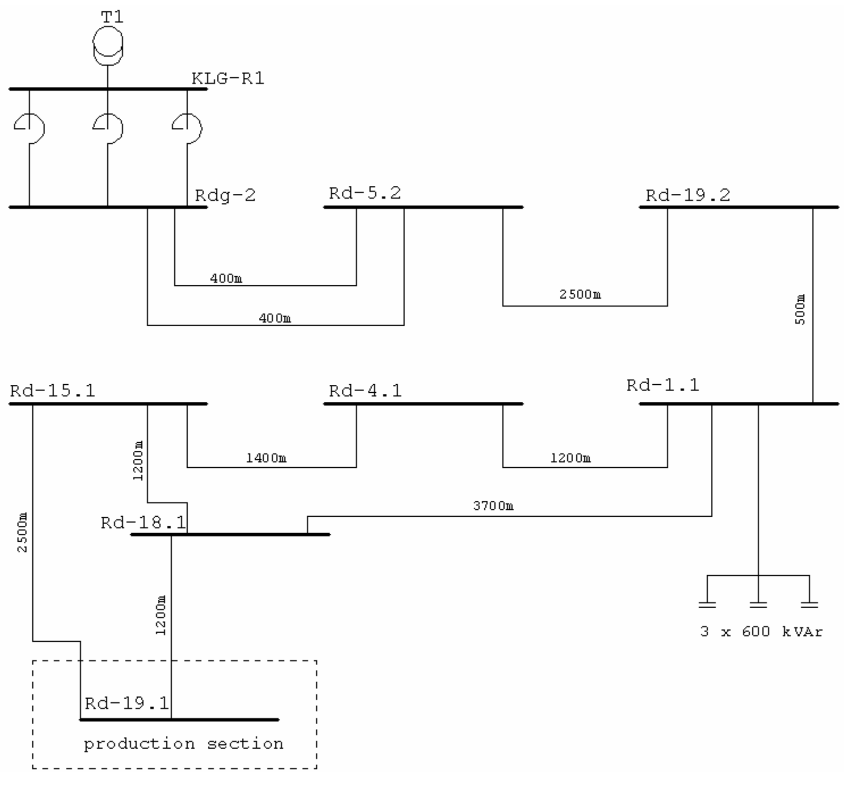

Fig. 3. Schematic diagram of the production section power supply

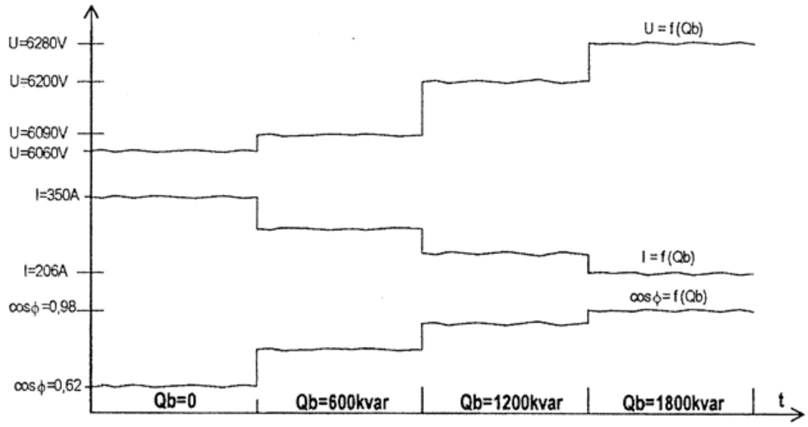

Fig. 4. Graphs of the voltage, current and power factor vs. time at P=const. and Q_b=var.

Calculation and selection of the capacitor bank rating was carried out employing results of the mine power system active and reactive power analysis.

The required capacitor power was determined from the formula:

$$Qb = P\,(\mathrm{tg}\varphi_1 - \mathrm{tg}\varphi_2)$$

where:
P = active power
$\mathrm{tg}\varphi_1$ = the actual value prior to compensation ($\mathrm{tg}\varphi = Q/P$)
$\mathrm{tg}\varphi_2$ = the value specified in the agreement with distribution company

Satisfactory results obtained during operation of the pilot capacitor bank (Fig. 5) justify the implementation of reactive power compensation in a broader range.

Reactive power compensation in mine underground networks

Several types of capacitor banks are presently in use in underground mines. Since the underground network supplies mostly three-phase balanced loads the implementation of reactive power compensation by means capacitor bank involves no particular technical problems. In such network either centralized or distributed compensation can be employed. Centralized compensation consists in reactive power compensation at a selected node of a power system. The distributed compensation is used to compensate reactive power drawn by individual loads. The choice between these two compensation systems depends on the network structure. In underground mines the most effective and economically viable is a centralized compensation system. Practical experience confirms advantageous technical and economic effects and good performance of central compensators provided with automatic control of reactive power.

Benefits from reactive power compensation

At current prices of electric energy the average cost of generating 1 MVAr of reactive power in rotating machines is ca. 8PLN. The calculation takes into account mainly fan motors and partly ball mill drive motors using the factor 40kW/lMVAr. At the actual demand of 10 MVAr this yields over 400 thousand PLN annually, excluding maintenance and repair costs due to worsened operating conditions of machines.

Fig. 5. Capacitor banks installed at the mine surface

Regarding the above the Lubin Mine management has taken decision to implement compensation of lagging reactive power by means of a capacitor bank. Initially, the approach to capacitors very careful concerning possible side effects of their operation, gradually they occurred to be easy in operation and maintenance, bringing significant technical and economic benefits. These are:

- ability of being installed at any point of the network,
- easy adaptation of the capacitor bank rated power to the actual demand
- very low active power losses ≤ 0.2W/kVAr, and
- easy assembly and maintenance-free operation.

Presently the Lubin Mine operates controlled capacitor banks of total power 13.5 MVAr, including 12.5 MVAr at 6kV and 1 MVAr at 500V networks what, adding the reactive power supplied from the CHP generator, balances the mine demand for reactive power. The benefits from reactive power compensation are substantial and quantifiable. They are:

1. <u>Increase of the concentration of output in the areas of the mine distant from the power supply sources</u>

2. <u>Increased transfer capability of transformers and lines</u>
   The transfer capability of transmission equipment results from its permissible temperature rise. In result of the reactive power flow the active power load should be reduced. The reduction is directly proportional to the power factor cosj. For example, at the power factor equal 0.6 a transformer rated 400 kVA can be loaded with power of only 240 kW (high harmonics are not taken into accounted). This issue can also be seen from a different point of view: how the transfer capability of a given network element increases when reactive power transmitted through this element is reduced. For example, if a transformer with rated power 400 kVA is operated at the 0.6 power factor, then increasing the power factor to 0.9 allows to increase its active power load from 240 kW to 360 kW, i.e. by 30%. Analogous relations apply to cables and overhead lines.

3. Improved voltage quality in the mine power system
   Voltage drops depend on both the reactive and active current component. Generally, in the mine conditions a large voltage drop is associated with fluctuations in supply voltage. Reduced voltage magnitude causes an increase in current (possible overheating, motor stalling) and reduction in rotational speed of induction motors, reduction in luminous flux of light sources, malfunction or failure of switching equipment with electromagnetic actuators, etc.
4. Improved operating conditions of the system elements
   A short-circuit current in a considerably under-compensated network tends more slowly to its steady-state value than the active current does. Interruption of current causes the occurrence of an arc between contacts of a breaker or a contactor. Arc quenching is much easier when the current is in phase with the voltage (active load). Therefore at the instant of the current zero crossing the voltage value at the contacts is also zero so there is no factor supporting the arc.

5. Deferred investments
   In the analyzed case the cost of 10 km of a 6kV cable line is ca. 3 500 000PLN, whereas the cost of a soft-start system is about 15 000PLN per 100 kW of rated power. Moreover, not all problems associated with power supply of distant production areas can be solved that way, particularly when power is delivered at the power factor value tgj=1.33 (cosj=0.60) and a short-circuit capacity at main underground switchboards is less than 100 MVA. The installation of reactive power compensation capacitors allows avoiding erection new cable lines to distant production areas and thus defer investments of 1¸2 mil PLN annually.

6. Reduction of transmission losses
   Active losses in supply network depend on the square of apparent power, i.e. on the sum of the squares of the active and reactive power transmitted. Calculations show that at cosj=0.7 active losses caused by the reactive power transmission exceed the losses resulting from active power transmission. Losses caused by the reactive power transmission considerably reduce the transmission system efficiency. A quantity characteristic for a given point in a supply network is the factor $F_{P/Q}$ that determines how the active power losses in kW, caused by the power flow from the source to that point, will be reduced per 1 kVAr reduction in the reactive power transmitted. This factor increases with the length of transmission line, the number of transformation stages and the load of supply network. The average value of the factor $F_{P/Q}$ in the mine network is 0.035 for 6kV and 0.1 for 500V network. Since the factor $F_{P/Q}$ increases with the distance to a given point of the network, the capacitor banks should be installed in locations most distant (in terms of the equivalent resistance) from the power sources. It is therefore evident that the most economically effective means of loss reduction is the reactive power compensation at the points of its generation, i.e. the production areas.

7. Reduction of additional charges paid to the distribution company for exceeding the tgj value specified in the agreement with distribution company
   The charge for the reactive energy surplus over the amount determined for the mine from the factor $tg\varphi_0$ is calculated from the formula:

$$C_R = 2\sum_{k=1}^{m} S_{Vnk}\left(\sqrt{\frac{1+(tg\varphi)_k^2}{1+(tg\varphi)_0^2}}-1\right)E_k$$

where:
C_R – charge for the surplus reactive energy, in PLN
S_{Vnk} – variable component of the use of system charge, relevant for the tariff group and *k*-th time zone, in PLN/kWh
$(tg\varphi)_k$ – power factor for the *k*-th time zone of the settlement period
E_k – active energy consumed in the *k*-th time zone, in kWh
m – number of settlement time zones
k – time zone.

Exceeding the agreed demand of reactive power from the power system (exceeding tgj) would result in an annual charge for the active energy consumed (depending on the surplus power level).

Economic and technical viability of the reactive power compensation in the Lubin Mine

Due to a large reactive power drawn by distributed underground loads a centralized compensation system has been selected. The system employs three-stage controlled capacitor banks with rated voltage 6 kV and power up to 1800 kVAr and controlled compensators with rated voltage 500 V and power 100 kVAr. The overall payback time of expenses for purchasing, assembly and commissioning of the compensation system in the Lubin Mine was three years of the compensated network operation.

Reactive power compensation and resonance effects

The occurrence of resonance phenomena should be taken into account when installing capacitor banks in a power system.
Electric circuits containing nonlinear components are sources of harmonics. With acceptable simplification generators and rotating compensators can be assumed the sources of harmonic voltages, whereas thyristor converters — the sources of harmonic currents. An additional source of harmonics, occurring in MV network can be the 110 kV network polluted with voltage harmonics by electricity consumers.
If a capacitor is connected in parallel with nonlinear loads then harmonic currents resonance may occur in the power supply network — capacitor bank. This results in the supply voltage distortion and the capacitor bank current overload.
The network inductance and the capacitance of capacitor bank (without line reactors) form a circuit with resonance frequency:

$$f_R = \sqrt{\frac{X_C}{X_S}} = f_{50Hz}\sqrt{\frac{S_{SC}}{Q_C}} = f_{50Hz} n_R$$

where:
X_C – capacitor bank capacitance,
X_S – equivalent reactance of the supply network (for the purpose of approximate calculations the network resistance was neglected)
S_{SC} – short-circuit capacity at the point of the capacitor bank connection
n_R – order of the resonance frequency f_R
Q_C – reactive power of the capacitor bank
f_{50Hz} = 50 Hz

Measurements carried out in the Lubin Mine shown that capacitor banks used for the reactive power compensation are not overloaded with harmonic currents. High harmonics sources, mainly 4 MVA 12-pulse thyristor converters with 5th, 7th and 11th harmonic filters in hoist mashies drives, have only a minor impact on the 6 kV distribution network.

Influence of capacitor banks on the earth current value and earth fault protection operation

Underground MV and LV networks in the Lubin Mine are operated in the IT system.

Since the capacitor banks are isolated from earth, their capacitance with respect to earth is very small and therefore they have no significant influence on the earth current value. In the case of earth fault the voltages values remain unchanged and, consequently, the currents drawn by the capacitor bank phase branches remain also unchanged. Since the capacitors installed in MV and LV networks operated in the IT system have only a minor influence on the earth current, the earth-fault protection can be selected in the same manner as before the capacitors installation.

Conclusion

The implementation of capacitor reactive power compensation in the Lubin Mine has produced the expected technical and economic effects. One should, however, be aware that compensation could be applied only to the level determined by reactive power demand. Currently this level in the Lubin Mine is 11□12 MVAr. In case of a significant increase of the concentration of output in the distant areas of the mine, other technical measures will be necessary. The objective of a currently undertaken study is to develop a technically and economically feasible method for power supply of distant production sections, which consists in their electrical separation. All concept studies of the power supply system development should also take into consideration rational management of reactive power in both the supply networks and the loads. The rational management of reactive power should be based upon a continuous monitoring of load and reactive power flow.

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