Improving Energy Efficiency in Mining Plant Using a Synchronous Motor

Radenko Marjanović
Arcelor Mittal Prijedor, d.o.o. Prijedor
Prijedor, Bosnia and Herzegovina

Petar Matić
Faculty of Electrical Engineering, Banja Luka, RS
Banja Luka, Bosnia and Herzegovina

Abstract - **This paper presents a case study for energy efficiency improvement by power factor correction using synchronous motor in the mining plant. Reactive power capability of a high voltage synchronous motor is investigated and limits related to terminal voltage and active power losses are pointed out. It is shown how under loaded synchronous motor can be successfully overexcited and used as reactive power source in order to improve efficiency. Limits regarding increased losses in the motor are investigated also. Practical example and measurement results are given.**

Keywords - synchronous motor, power factor correction, energy efficiency.

I. INTRODUCTION

Most electrical devices, except synchronous machine with its own excitation and some collector machines have to be supplied by reactive power from the network. The largest consumers of reactive power are induction motors and transformers. Inappropriate selection of induction motors and transformers (over sizing or under loading) can cause power factor to be lower than acceptable. Low power factor decreases the efficiency of the whole plant. In present days major part of reactive energy can be economically compensated by using reactive power sources. Compensation should be installed close to the major consumers of reactive power (distributed compensation), or as close to the main point of consumption (central compensation) [1, 2].

Reactive energy compensation is usually realized by using capacitor banks. In large industrial plants, such as mining plant, synchronous motors which normally drive large loads like pumps, can be overexcited and used as reactive energy sources. Reactive power capability of a synchronous motor is limited by active load, excitation current (thermal limits) and by terminal voltage. Those limits are investigated for one 6kV 1250kW synchronous motor used for driving a pump in the mining plant. It is shown how to calculate reactive power capability for a given operating regime. Practical results gathered on the Mine plant “Omarska” are presented. It is shown that energy efficiency can be improved by properly overexciting synchronous motor.

II. POWER FACTOR CORRECTION BY USING A SYNCHRONUOS MOTOR

Synchronous motor is the only machine that offers power-factor correction while performing the main driving function, like running a pump or plant compressor [3]. By adjusting the motor excitation, reactive power production can be changed without the influence to the active power flow. By changing the excitation current, stator current either lags, or leads the voltage vector. In the same time, since the motor torque is not changed, reactive power compensation can be obtained. The balance between active and reactive power is limited by maximum stator current, maximum rotor current, and by terminal voltage. These limits are usually represented by operating chart of the machine as shown in Fig. 1 [3, 4].

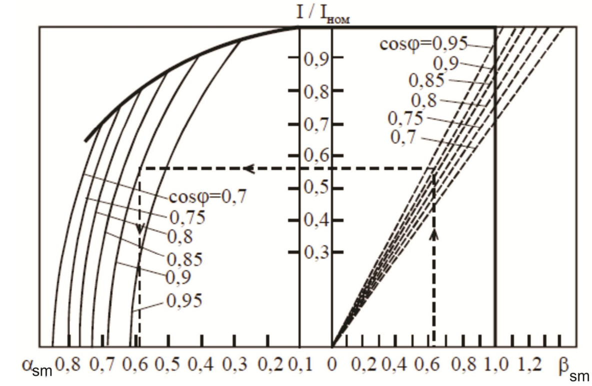

Figure 1. Modified Operating Chart of Synchronous Machine

If synchronous motor is under loaded

$$\beta_{sm} = P / P_{nom} < 1 \tag{1}$$

where β_{sm} is coefficient of load active power, P_{nom} is nominal output power, than the reactive power can be increased above rated level. The reactive power Q_{sm} for rated power factor (angle φ_{nom}), efficiency η and given load β_{sm} is calculated as:

$$Q_{sm} = \frac{\beta_{sm} P_n \tan\varphi_n}{\eta} \tag{2}$$

and is the reactive power for given load and rated power factor. If machine is underloaded with rated power factor, reactive power Q_{sm} is lower than rated reactive power.

Reactive power can be increased by increasing the excitation current. For given load (coefficient β_{sm}) and given power factor, coeffitient α_{sm} is first found from Fig. 1. Than, reactive power Q_{smR} for given load and given power factor is found as:

$$Q_{smR} = \alpha_{sm} S_n = \alpha_{sm} \sqrt{P_n^2 + Q_n^2} \, . \tag{3}$$

where α_{sm} is the coefficient of the synchronous motor overload capacity, determined from Figure 2.

Maximum value of reactive power is limited by excitation current and terminal voltage. Usually, maximal excitation current is equal to the rated value, and this limit can be assumed constant. If the excitation current is kept constant, reactive power capability varies only with terminal voltage. By increasing the voltage, machine consumes more reactive power for magnetizing, and can supply less reactive power on the output (and vice versa) [4, 5]. The influence of terminal voltage to reactive capability is given by equation:

$$Q_{smMAX} = \frac{K_{rof} P_n \tan \varphi_n}{\eta} \tag{4}$$

where K_{rof} is reactive power overload coefficient, which depends on the motor load β_{sm} and terminal voltage. This coefficient for a given motor can be found from Table I.

TABLE I. COEFFICIENT K_{ROF} FOR SYNCHRONOUS MOTOR СДНЗ-16-41-12У3

Type of synchronous motor	The relative voltage at the motor terminals Urel	Reactive power overload coefficient Krof at load factor βsm		
		0,9	0,8	0,7
СДНЗ-16-41-12У3	0,95	1,31	1,39	1,45
	1	1,21	1,27	1,33
	1,05	1,06	1,12	1,17
	1,1	0,88	0,92	0,94

Based on Table I and nominal data of synchronous motor СДНЗ-16-41-12У3, the dependence between reactive power and terminal voltage can be presented as in Figure 2.

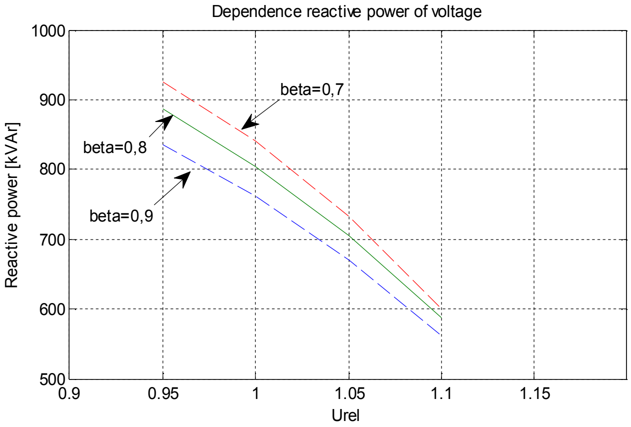

Figure 2. Reactive Power Production vs. Relative Votage

From Figure 2 it can be seen that at the constant load, maximal production of reactive power deecreases as voltage increases This corresponds to the operating chart from Fig. 1.

By increasing reactive power of motor, active power losses ΔP_{sm} increase. Active power losses ΔP_{sm} depend on rated power P_n and speed: the lower rated active power and speed of synchronous motor, the losses are higher [4]. For given speed active power losses can be calculated as a function of produced reactive power Q [4]:

$$\Delta P_{sm} = \frac{D_1}{Q_n} Q + \frac{D_2}{Q_n^2} Q^2 \tag{5}$$

where Q is generated reactive power of synchronous motor, D_1, D_2 are constant coefficients that depend on motor parameters, whose values are given in Table II.

TABLE II. COEFFICIENTS D_1 AND D_2 FOR THE SPECIFIC TYPE OF SYNCHRONOUS MOTOR

Type of synchronous motor	Coefficients D_1 and D_2	
	D_1	D_2
СДНЗ-16-41-12У3	8,44	6,09

Formula (5) shows the dependance of active losses increase as function of the production of reactive power kW/kVAr. For Q=0 active losses are $\Delta P_{sm}=0$.

Based on (5) and Table II, active power losses as function of the reactive power production can be shown as in Figure 3. From Fig. 3 it is clear that the increase in reactive power is followed by increase in losses. This effect should be taken into account when synchronous motor is used for improving the efficiency as reactive power source.

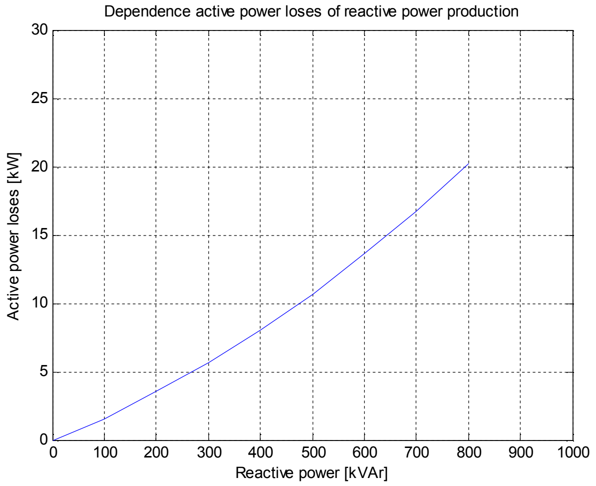

Figure 3. Dependence of Active Power Losses Increase vs. Reactive Power Production

III. MINING PLANT "OMARSKA"

Mining plant is powered from a 110/6 kV 16MVA transformer station (Figure 4). There are three supply lines, two in the gravity-magnetic separation and one for the open pit mine. Gravity-magnetic separation plant has rated power of 3.5 MW while rated power of the open pit is 2.5 MW.

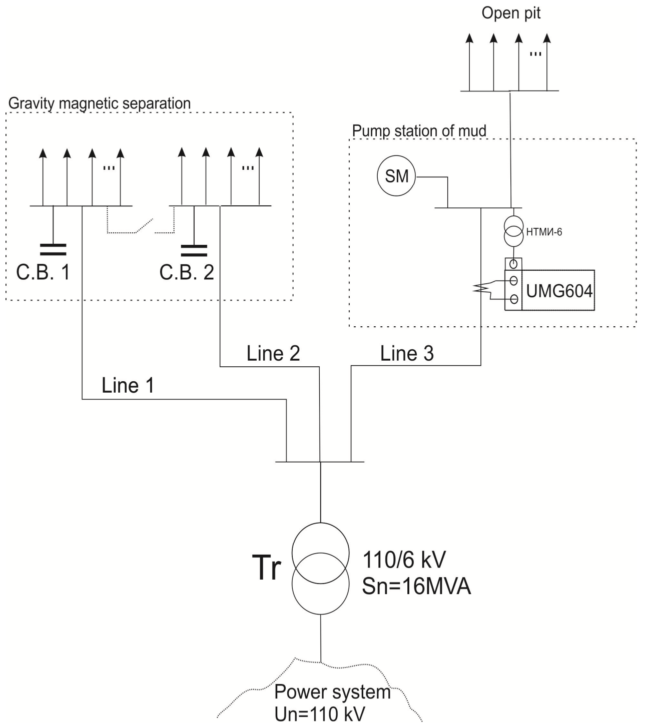

Figure 4. Single Line Diagram Scheme of the 6kV Plant

Synchronous motor SM runs the pump in mud pump station located at the beginning of the supply cable in the open pit mine. The length of the Line 3 is approx. 3,5 km.

Reactive power is compensated by two capacitor banks located in the 6kV substation of gravity-magnetic separation. Reactive power capacities of banks C.B.1 and C.B.2 are 1250 kVAr, and 2000 kVAr respectively. The pump is driven by synchronous motor type СДН3-16-41-12У3 with nominal data: 1250 kW, cosφ=0,9, n=500 rpm, η= 94,78 % Y, U= 6000 V, I= 140 A, rotor data U= 67 V ,I= 250 A. From the nominal data and given load, β_{sm} and α_{sm} are calculated and given in Table III.

TABLE III. COEFFITIENTS FOR THE SYNCHRONOUS MOTOR СДН3-16-41-12У3 FOR THE GIVEN OPERATING REGIME

P_{nom}	P_{real}	Q_{nom}	β_{sm}	α_{sm}	Q_{smR}
1250 kW	1000 kW	637 kVAr	0,8	0,52	729,53 kVAr

IV. MEASURING RESULTS

The goal of the paper is to show how plant efficiency can be improved by overexciting the synchronous motor. Two regimes were under the scope: first, when SM from Fig. 4 operates with unity power factor, and the second, when SM is overexcited and reactive power on Line 3 is fully compensated. During the measurement, mining plant was operating at rated capacity.

Total duration of the measurements was about 20 minutes. The first measurement was performed in a time interval of 10 minutes when the synchronous motor was working with unity power factor. After that, excitation of synchronous motor is gradually increased up to value when synchronous motor fully compensates reactive power on Line 3.

Measurements were performed using measurement device Janitza UMG604 shown in Figure 4. Measuring device is connected by current transformers, ТПЛ10 type, with ratio 200/5 A, accuracy class 0.5 and voltage measuring transformers, type НТМИ-6, with the transfer ratio 6000/100 V and accuracy class 1.

Active and reactive powers are shown in Figs 5 and 6, current and voltage are shown in Figs 7 and 8, while THDu is shown in Fig 9.

From Fig. 5 it can be seen that load on Line 3 was almost constant during the measuring. From Fig. 6 it is clear that reactive power on Line 3 decreased almost to zero when SM was overexcited. This resulted in current (Fig. 7) to decrease since there was no reactive power flow on Line 3. Since the current was decreased, active power losses in Line 3 were decreased. From Figs 8-9. it is clear that changes in SM reactive power production did not have significant influence to line voltage and THD.

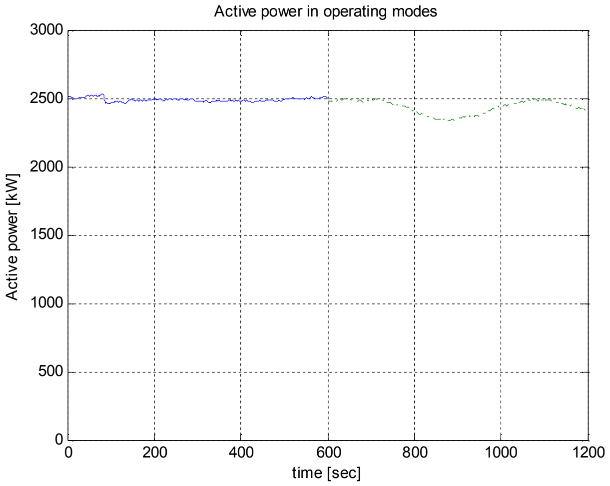

Figure 5. Active Power on Line 3 in Operating Mode 1 (line '-'), and in Mode 2 (line '--')

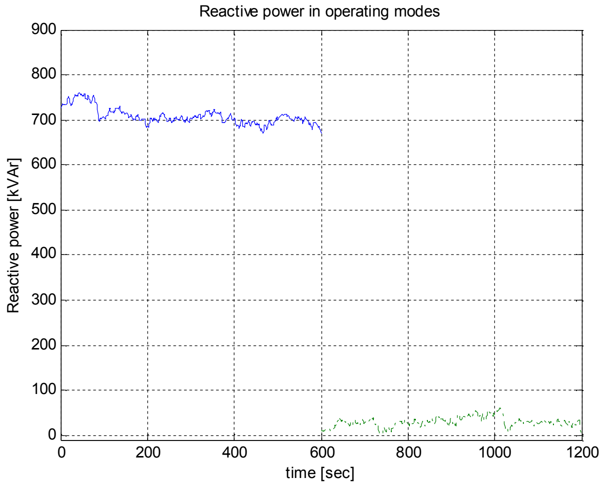

Figure 6. Reactive Power on Line 3 Operating Mode 1 (line '-‘), and in Mode 2 (line '--')

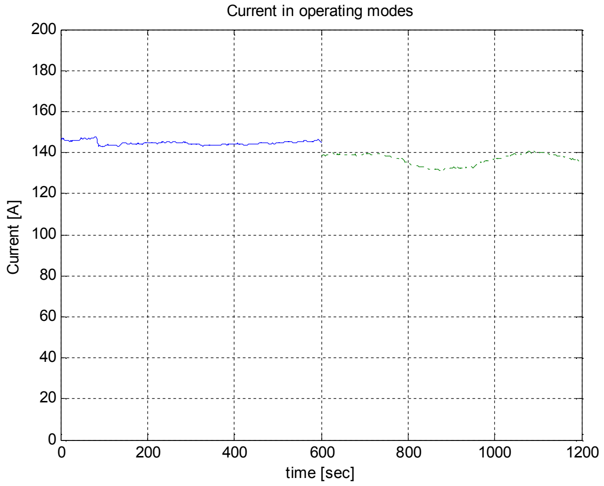

Figure 7. Current on Line 3 in Operating Mode 1 (line '-'), and in Mode 2 (line'--')

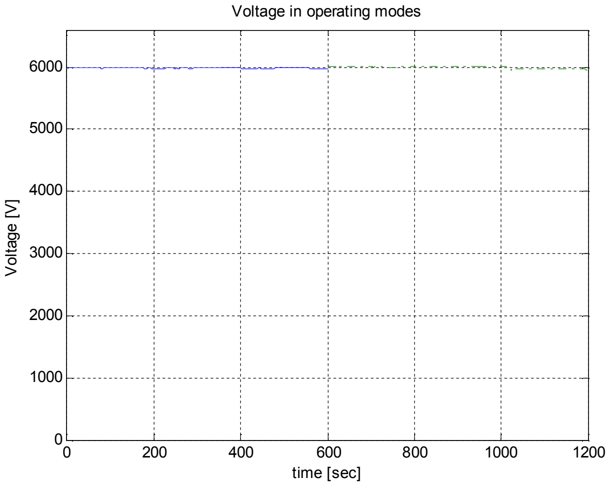

Figure 8. Voltage on Line 3 Operating Mode 1 (line '-'), and in Mode 2 (line '--')

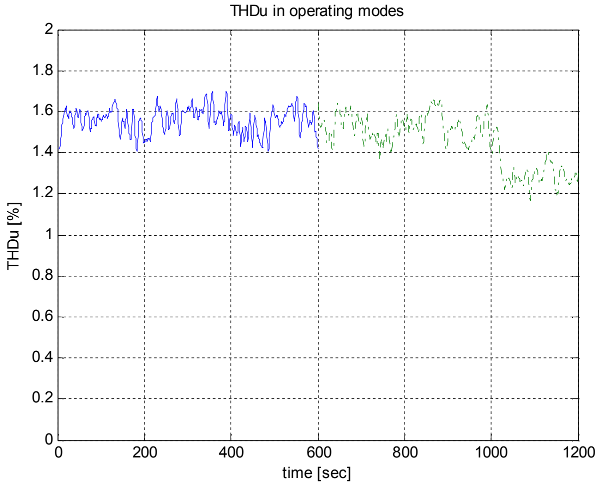

Figure 9. THDu on Line 3 in Operating Mode 1 (line '-'), and in Mode 2 (line '--')

Based on measuring shown in Figures 6 - 10. the mean value of the measured variables during the test period are calculated and shown in Table IV.

TABLE IV. MEAN VALUES OF MEASURED PARAMETERS ON LINE 3

	LINE 3				
	P [kW]	Q [kVAr]	I [A]	U [V]	TDHU [%]
Mode 1	2489,29	708,21	249,6	5985,54	1,56
Mode 2	2435,99	29,51	234,6	5994,25	1,45

V. EFFICIENCY IMPROVEMENT

Based on the measurements, the energy efficiency improvement can be calculated for the Line 3 when using synchronous motor for reactive power compensation.

Synchronous motor in operating mode 1 was producing about 70 kVAr of reactive power. On the basis of formula (5) active power losses due to excitation was:

$$\Delta P_{sm}=\frac{D_1}{Q_n}Q+\frac{D_2}{Q_n^2}Q^2=\frac{8,44}{637}70+\frac{6,09}{637^2}70^2=1kW \quad (6)$$

The network was fully compensated when the excitation was increased up to the level when the reactive power was approx. 700 kVAr (operating mode 2). Active losses in synchronous motor due to increased reactive power production are increased up to:

$$\Delta P_{sm}=\frac{D_1}{Q_n}Q+\frac{D_2}{Q_n^2}Q^2=\frac{8,44}{637}700+\frac{6,09}{637^2}700^2=16,5kW \quad (7)$$

Active losses of motor due to increasing production of reactive power increased by 15,5 kW.

The losses in the cable on the Line 3 were:

$$P_{losses}=3RI_{o.m.1}^2=149,5kW \quad (8)$$

where

R=0,8 Ω is total resistance of cable.

In operating mode 2 current through the cable was decreased, and the losses in the cable were:

$$P_{losses}=3RI_{o.m.2}^2=132,1kW \quad (9)$$

Differences in cable losses between the two operating modes is 17,4 kW.

Since the current was decreased, active losses in the transformer changed. Transformer resistance was:

$$R_T=\frac{r_{T[\%]}}{100}\frac{U^2}{S_n}=\frac{3}{100}\frac{6000^2}{16\cdot 10^6}=0,07\Omega \quad (10)$$

where R_T is resistance of transformer, and S_n rated power. Losses in transformer have reduced due to a decrease of current in operating mode 2 for

$$\Delta P_{transformer}=3R_T(I_{o.m.1}^2-I_{o.m.2}^2)=3\cdot 0,07\cdot 7263=1,52kW \quad (11)$$

The final balance of the losses shows that the losses in the cable are reduced while the losses in the synchronous motor were increased. Total loss reduction with increasing production of reactive power is:

$$\Delta P_{losses}^{total}=\Delta P_{losses}^{cable}+\Delta P_{losses}^{transformer}-\Delta P_{losses}^{sm}=17,4+1,52-15,5=3,42kW \quad (12)$$

Since synchronous motor operates approx. 4200 hours a year, and the price of electricity paid by the mine is 0.065 KM / kWh, the annual savings obtained by the production of reactive power with synchronous motor are:

$$C_e=\Delta P_{losses}^{total}\cdot c_e\cdot T=3,42\cdot 0,065\cdot 4200=934KM \quad (13)$$

Participation of losses in the production of reactive power in synchronous motor [6] when operating in mode 2 is:

$$\frac{\Delta P_{sm}}{Q_{o.m.2}}[\%]=\frac{16,6}{700}\cdot 100\%=2,3\% \quad (14)$$

Participation of losses in the production reactive power with synchronous motor is 2,3%.

VI. CONCLUSION

In the paper it is investigated reactive capability of high voltage synchronous motor depending on operating mode and demanded reactive power production. It is shown how the production of reactive power for under loaded motor can be increased up to the limit defined by maximum excitation current. Production of reactive power decreases when voltage increases, and this limit is included into the study also. The investigation is supported by measurement data obtained from the open pit mine plant.

Synchronous motor is overexcited in order to fully compensate reactive power on the supply line. The losses in the line and supply transformer are reduced, while losses in the motor are increased. In total, losses are reduced. Significant improvement of the efficiency is obtained without any investment costs, since the compensation is made only by changing the excitation current. Total losses are both decreased and reallocated from the cable into the synchronous motor.

REFERENCES

[1] Igor Kuzle, “Kompenzacija jalove snage,“ Fakultet elektrotehnike i računarstva Zagreb, 1988.

[2] Nikola Rajaković, Dragan Tasić, Gojko Savanović, “Distributivne i industrijske mreže,” Akademska misao Beograd, 2004.

[3] Branko Mitraković, “Sinhrone mašine,“ Nauka, Beograd, 1989.

[4] А.В. Кабышев, С.Г. Обухов, “Расчет и проектирование систем электроснабжения объектов и установок,“ Издательство ТПУ Томск, 2006.

[5] Jasna Dragosavac, Žarko Janda, Jelena Pavlović, Tomislav Gajić, Dušan Arnautović, Bojan Radojičić, “Exploiting of Generator Reactive Capability,“ Conference Proceedings of the 16th International Symposium on Power Electronics - Ee 2011, Novi Sad, October 26-28.2011.

[6] А.Е. Веселов, А.С. Карпов, В.В. Ярошеви, “Технико-экономическая оценка эффективности привлечения синхронных электродвигателей предприятий к генерации реактивной мощности,“ Вестник МГТУ, 2009.