Mining of Mineral Deposits
Volume 16 (2022), Issue 2, 73-80

MMD JOURNAL / MINING.IN.UA

https://doi.org/10.33271/mining16.02.073

Identifying the factors influencing the voltage quality of 6kV grids when using electric excavators in surface mining

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Abstract

Purpose. The research purpose is to study the relationship between the number of electric excavators and their impact on reducing the voltage losses. As a result of the research, it becomes possible to obtain factors that can help the manager to correctly understand the effect of power compensation caused by the over-excitation mode of electric excavators.

Methods. The paper uses the Jacobian matrix transformation to simulate the power flows of electric excavators, the driving mechanisms of which are mainly synchronous motors. The input data for the simulation is the in-situ measurement data representing the inverse power flow. A diagram and a software to determine the factors corresponding to the number of electric excavators are also provided.

Findings. A cross-reference table has been compiled showing the ratio of factors corresponding to the number of electric excavators in a 6kV grid. An appropriate software has also been developed, including a table for correcting typical equations for calculating voltage losses.

Originality. The proposed factor is conditioned by over-excitation mode of excavators operating as compensation machines in a 6kV grid.

Practical implications. When calculating the voltage loss in a 6kV grid of surface mines, if the design feeder contains electric excavators, a modified factor should be added to give a correct idea of the voltage quality.

Keywords: *electric excavator, voltage quality, over-excitation mode, Jacobian matrix transformation, open-pit mining*

1. Introduction

In the 6kV grids of Vietnam surface coal mines, power quality (PQ) problems are not new, but only recently the consequences of these problems have gained public attention, as well as much attention from operators. Due to an increase in the output capacity, the number of electric excavators is increasing rapidly. The use of these high capacity loads in mining practice also causes the PQ violations as well as voltage quality violations. Many studies have shown that in surface mines, electric excavators (EEx) with high capacity loads can significantly affect the voltage quality. However, none of them are mentioned by number, and the total apparent power of EEx in some typical surface mines in Vietnam is given in Table 1 [1], [2].

Table 1. Number and total apparent power of EExs in typical surface coal mines

Year	Cao Son		Coc Sau		DeoNai		NuiBeo	
	Num	Σ*S*, kVA	Num	Σ*S*, kVA	Num	Σ*S*, kVA	Num	Σ*S*, kVA
2017	16	8246	18	5814	12	3876	3	885
2018	18	8550	18	5814	12	3876	4	1180
2019	17	8350	18	5814	13	4035	4	1180
2020	18	8725	20	6563	15	5145	6	1770

As can be seen from Table 1, the number of EEx in surface coal mines of Vietnam has grown rapidly because, according to the estimated data presented in the energy consumption report, these devices consume from 40% to 65% of the total electrical energy of coal mining companies [1]. In electrical energy diagram (6kV grids), all electric excavators are powered by a single feeder with a few PCC nodes (skeleton diagram). The improper connection of such high capacity loads in a 6kV grid can lead to temporary overload. Therefore, it is necessary to take into account the operating mode of excavators when analyzing voltage quality.

At present, most of the excavators in Vietnam's surface mines are electric ones, which are equipped with synchronous motors as the main driving mechanism [3]-[5]. During a cycle of digging operations, these types of motors may have a reverse power during lowering or slewing stoppage [6]. Table 2 shows the specification of driving motors on EEx.

It could be seen that the 6kV synchronous motor (SyM) on EEx is the main energy consumer that is responsible mainly for digging in cycles.

Many studies [7]-[12] showed the dynamic performance as well as the energy consumption by EEx. All 4 main parts of EEx are examined to show a general moving as well as all positions of bucket, stick, boom cylinders, and angles of swing system (Fig. 1).

Received: 3 December 2021. Accepted: 11 May 2022. Available online: 30 June 2022

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

Table 2. Specification of driving motors on EEx

Name	Type of driving system	U_{nom}, kV	P_{nom}, kW	cos φ
EKG 4,6 A and 5A	3 phase SyM	6	250	0.86
	Air pressure motor	0.22	15	0.85
	Cooling Fan motor	0.22	2.2	0.85
	Cooling Fan motor	0.22	1.5	0.85
	Oil pumping motor	0.22	1.5	0.85
EKG8Y	3 phase SyM	6	560	0.89
	Motor of auxiliary motor	0.38	40	0.85
	Air pressure motor	0.38	15	0.85
	Cooling Fan motor	0.38	2.2	0.85
	Cabin Ceiling fan motor	0.38	3	0.85
EKG10A	3 phase SyM	6	750	0.89
	Motor of auxiliary motor	0.38	40	0.85
	Air pressure motor	0.38	15	0.85
	Cooling Fan motor	0.38	2.2	0.85
	Cabin Ceiling fan motor	0.38	3	0.85

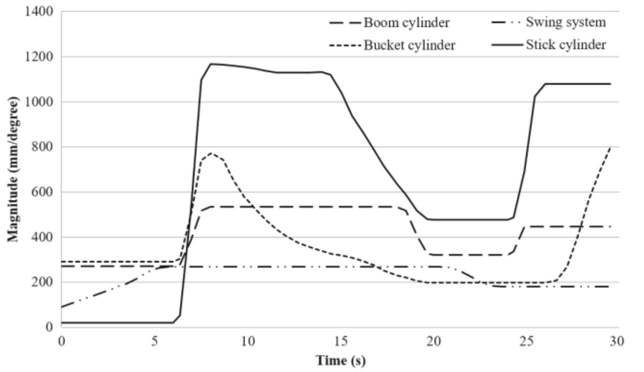

Figure 1. Working cycle diagram for bucket, stick, boom cylinders and swing system

Based on the working cycle analysis, many dynamic models have been built to get driving moments of the components and energy consumption during the boom operation (Figs. 2 and 3).

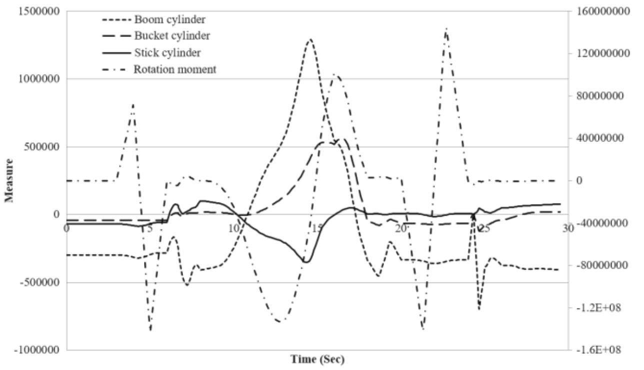

Figure 2. Driving forces/moment diagram for bucket, stick, boom cylinder and swing system

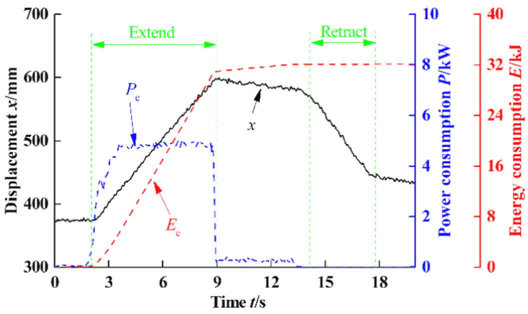

Figure 3. Energy consumption of the excavator during the boom operation [9]

The kinematics and dynamics of excavators are also calculated [9], [10], [12]. However, the calculation results show that the EEx digging operations (lowering or slewing procedure) contain negative power flows and negative electromagnetic torque (Figs. 4 and 5). During these time intervals, EEx act as a power source that that supplies power to the 6kV grid rather than load.

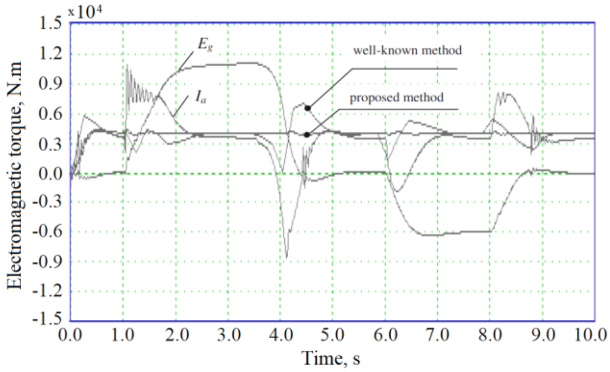

Figure 4. Simulation results of a mining shovels cycle with a bucket capacity of 5.0 m³ (PU) [13]

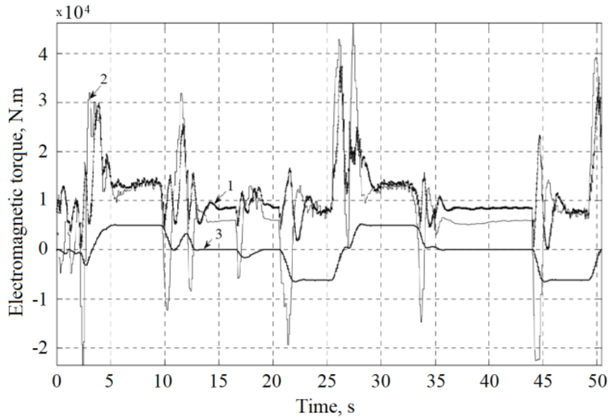

Figure 5. Electromagnetic torque of hoist bucket mechanism electric drive: 1 – for the α-β coordinate system arbitrary orientation, N·m; 2 – for the α-β coordinate system orientation of the rotor flux vector, N·m; 3 – wr (angular frequency of the rotor rotation), RPM×10 [13]

These specific working characteristics of the EEx driving system are indicated in many studies [8]-[10], [14]-[16]. These studies indicate that the energy saving level of EEx is great due to the recovery of the potential energy or a kinetic energy during lowering or slewing stoppage. This is mainly caused by the digging process, which significantly influences on the mechanic and kinetic parameters of the EEx itself.

The energy saving efficiency of EEx is determined in the range from 20 to 30%, taking into account the individual consideration of each excavator [15], [17], [18].

It is obvious that when operating EEx as power sources, the voltage quality of the feeders to which they are connected can be improved. Their electrical energy can power loads around PCC (point of couple connection) nodes. The next section of this paper gives the analysis of this special operating mode to reduce the voltage drop.

2. Simulation of the energy recovery of excavators

To estimate the impact of special working mode of EExs, the following steps are implemented. Each EEx must be simulated on Matlab to understand about their reverse power flows at the moment of lowering or slewing stoppage. The onsite measurements are implemented individually with each excavator to verify the precise of simulation model.

In final stage, each energy consumption of a single feeder with connected electric excavators is measured. The results are compared with theoretical computation to deduct the modifying/correction factors that obtain the decrease level corresponding to the number of electric excavators. To assist the calculation process, a software is established with application of Jacobian matrix transformation.

2.1. Simulation the operation of synchronous motor on excavator

To describe the flux ratio in a synchronous motor, a matrix Equation is shown in 1 [19], [20]. Theoretically, flux reaction on the synchronous motor rotor is presented in the form of space-vector equations (Eq. 2) [21].

$$\begin{bmatrix} U_{as} \\ U_{bs} \\ U_{cs} \\ U'_{ar} \\ U'_{br} \\ U'_{cr} \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 & 0 & 0 & 0 \\ 0 & r_s & 0 & 0 & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 & 0 \\ 0 & 0 & 0 & r_s & 0 & 0 \\ 0 & 0 & 0 & 0 & r_s & 0 \\ 0 & 0 & 0 & 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i'_{ar} \\ i'_{br} \\ i'_{cr} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{as} \\ \lambda_{bs} \\ \lambda_{cs} \\ \lambda'_{ar} \\ \lambda'_{br} \\ \lambda'_{cr} \end{bmatrix}; \tag{1}$$

$$\bar{V}_s = r_s \bar{i}_s + \frac{d\bar{\psi}_s}{dt} + j\omega_r \bar{\psi}_s;$$

$$\bar{i}_s = i_d + ji_q;$$

$$\bar{\psi}_s = L_d i_d + L_{dm} i_F + jL_q i_q;$$

$$V_F = r_F i_F + \frac{d\psi_F}{dt};$$

$$\psi_F = L_F i_F + L_{dm}\left(i_d + i_F\right);$$

$$T_e = \frac{3}{2} p_1 r_e \left(j\bar{\psi}_s i_s^*\right) = \frac{3}{2} p_1 \left[L_{dm} i_q i_F + \left(L_d - L_q\right) i_q i_d\right]. \tag{2}$$

Equation 1 $[\lambda]$ shows the total flux as a matrix calculated from the stator and rotor inductance. Using Clarke transform [22], the currents of phase a, phase b and phase c are converted into *d*, *q*, 0 axes, the final equation expressing voltage-currents in the main motors of the 6kV electric excavator is presented in Equation 3. The others represent the torque and power of motor, shown in Equations 4 and 6.

Based on Equations 2-6, the main EEx driving system is simulated and shown in Figure 6. For obtaining the reaction of special operating mode of synchronous motors as a compensation power source [20], the sign of T_{mech} in Equation 3 must be minus (negative torque).

$$\begin{bmatrix} r_s & w\left(L_{ss} + \frac{3}{2}L_m\right) & 0 & 0 & \frac{3w}{2}L_m & 0 \\ -w\left(L_{ss} + \frac{3}{2}L_m\right) & r_s & 0 & \frac{-3w}{2} & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 & 0 \\ 0 & \frac{3\left(w - w_m\right)}{2}L_m & 0 & r_r & \left(w - w_m\right)\left(L_{qr} + \frac{3}{2}L_m\right) & 0 \\ \frac{-3\left(w - w_m\right)}{2}L_m & 0 & 0 & -\left(w - w_m\right)\left(L_{sr} + \frac{3}{2}L_m\right) & r_r & 0 \\ 0 & 0 & 0 & 0 & 0 & r_r \end{bmatrix} \times$$

$$\times \begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{0s} \\ v_{qr} \\ v_{dr} \\ v_{0r} \end{bmatrix} + \begin{bmatrix} L_{\sigma r} + \frac{3}{2}L_m & 0 & 0 & \frac{3}{2}L_m & 0 & 0 \\ 0 & L_{\sigma r} + \frac{3}{2}L_m & 0 & 0 & \frac{3}{2}L_m & 0 \\ 0 & 0 & L_{\sigma s} & 0 & 0 & 0 \\ \frac{3}{2}L_m & 0 & 0 & L_{\sigma r} + \frac{3}{2}L_m & 0 & 0 \\ 0 & 0 & 0 & 0 & L_{\sigma r} + \frac{3}{2}L_m & 0 \\ 0 & 0 & 0 & 0 & 0 & L_{\sigma r} \end{bmatrix} \times \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{0s} \\ i_{qr} \\ i_{dr} \\ i_{0r} \end{bmatrix} \tag{3}$$

The accelerating torque equation:

$$T_{acc} = T_{em} + T_{mech} - T_{damp} = J\frac{d\omega(t)}{dt} = \frac{2J}{P} \cdot \frac{d\left[\omega_r(t) - we\right]}{dt}, \tag{4}$$

where:

T_{em} – electromechanic torque.

$$T_{em} = \frac{3}{2} \cdot \frac{P}{2}\left(L_d - L_q\right) \cdot i_d \cdot i_q + \frac{3}{2} \times \\ \times \frac{P}{2}\left(L_{md} \cdot i'_{kd} \cdot i_q - L_{md} \cdot i'_{kq} \cdot i_d\right) + \frac{3}{2} \cdot \frac{P}{2} L_{md} \cdot i'_m \cdot i_q. \tag{5}$$

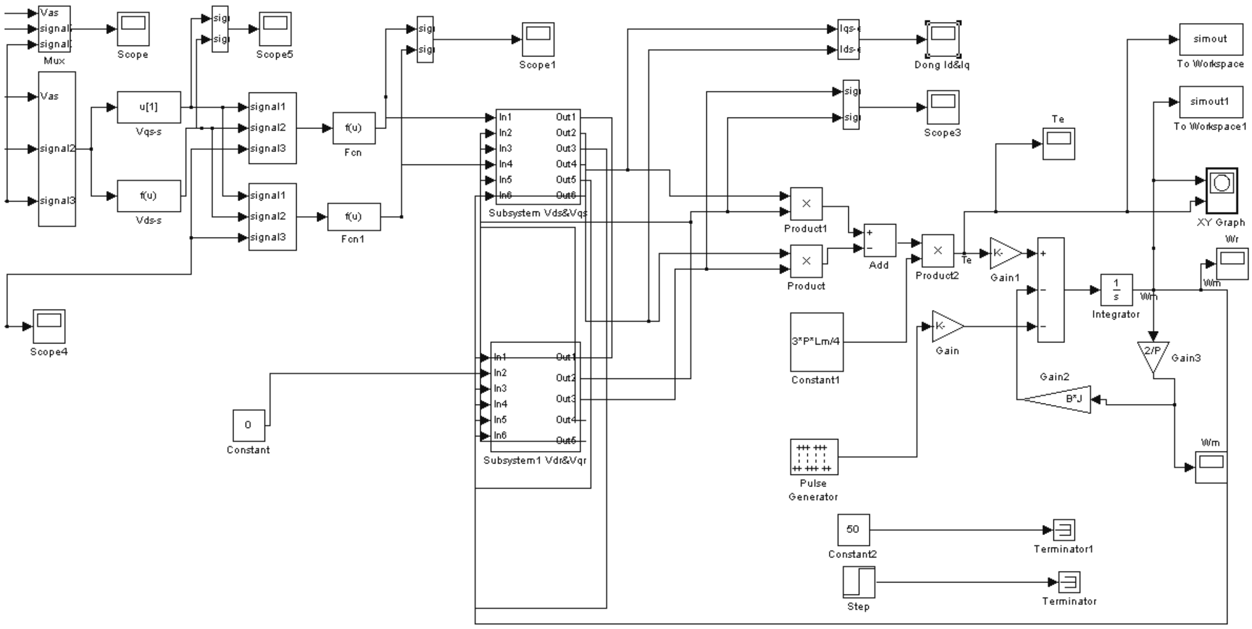

Figure 6. Simulation of driving system on a synchronous motor of an electric excavator

The equation of active and reactive power delivered by motor:

$$|V_t| = \sqrt{V_{qs}^2 + V_{ds}^2}\ ;$$

$$|V_t| = \sqrt{I_{qs}^2 + I_{ds}^2}\ ;$$

$$P = R_{eal}\left[\left(v_q - jv_d\right)\left(i_q - ji_d\right)^*\right] = v_q i_q + v_d i_d\ ;$$

$$Q = I_m\left[\left(v_q - jv_d\right)\left(i_q - ji_d\right)^*\right] = v_q i_q + v_d i_d\ . \qquad (6)$$

The results obtained from the simulation of electric excavators are shown in Figures 7 and 8 (implemeted with motors at the Cao Son and Coc Sau open-pit coal mines of Vietnam).

In Figures 7 and 8, there are time intervals showing the power below the zero line. This means that at these moments the excavators do not deliver power from the source, but they operate as a source for supplying energy to the grid. Therefore, they play the role of improving the power quality in the grid.

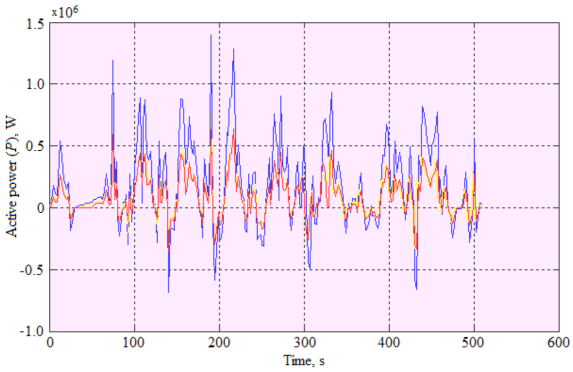

Figure 7. Three-phase active power of EKG8A, simulated on PCC node of the Coc Sau open-pit coal mine

2.2. On-site verification of special operating mode of excavators

The illustration from the above simulation is veryfied by on-site mesurements. Using real-time meters, the results of the active power consumed by electric excavator are shown in Table 3. Other representation of this power is shown in Figures 9 and 10.

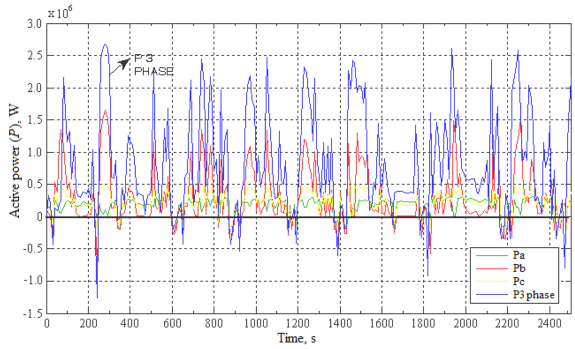

Figure 8. Three-phase active power of EKG8A, simulated on PCC node of the Cao Son open-pit coal mine

Table 3. On-site measurement at the Cao Son and Coc Sau open-pit coal mines in Vietnam

Date	Time	Elapsed time	P_{inst}, W	$P1_{inst}$, W	$P2_{inst}$, W
9/20/2019	15:18:23	0:00:17	22.260	17.740	0
9/20/2019	15:18:24	0:00:18	54.540	34.520	23.010
9/20/2019	15:18:25	0:00:19	181.200	98.680	84.530
9/20/2013	15:18:26	0:00:20	117.700	63.160	47.520
9/20/2019	15:18:27	0:00:21	111.300	57.650	42.540
9/20/2019	15:18:28	0:00:22	236.200	124.900	112.100
9/20/2019	15:18:29	0:00:23	537.600	255.100	257.800
9/20/2019	15:18:30	0:00:24	416.800	214.300	196.400
9/20/2019	15:18:31	0:00:25	228.600	121.000	108.600
9/20/2019	15:18:32	0:00:26	182.800	98.740	83.070
9/20/2019	15:18:45	0:00:39	155.500	84.810	71.560
9/20/2019	15:18:46	0:00:40	221.200	109.200	91.220
9/20/2019	15:18:47	0:00:41	-176.200	-82.760	-113.300
9/20/2019	15:18:48	0:00:42	-125.000	-51.730	-66.250
9/20/2019	15:18:49	0:00:43	66.040	36.500	27.540
9/20/2019	15:18:50	0:00:44	68.130	41.490	28.530
9/20/2019	15:18:51	0:00:45	82.530	48.380	35.040
9/20/2019	15:18:52	0:00:46	83.930	47.380	36.550
9/20/2019	15:18:53	0:00:47	87.950	51.480	39.570

Figures 9 and 10 present the three-phase active power, as well as the total (P_{sum}) deliveried by the excavators. As in Table 3, there are also periods of time when the "P" value is below the zero line.

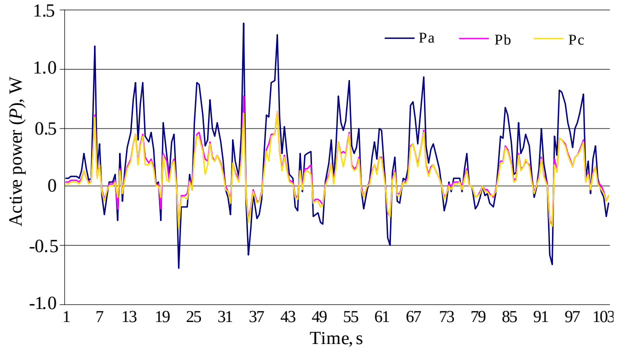

Figure 9. Three-phase active power of EKG8A, simulated on PCC node of the Cao Son open-pit coal mine

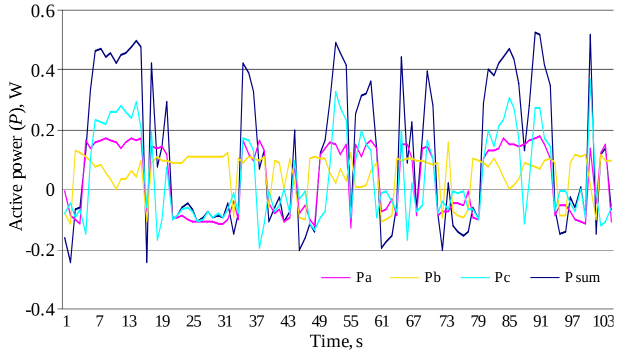

Figure 10. Three-phase active power of EKG8A, simulated on PCC node of the Cao Son open-pit coal mine

This effect is called "regenerating braking operation". The figures ones again prove the confirmation of delivered power of EEx as an individual source. Therefore, when there are more EEx on the feeder, their impact on the voltage quality improvement is significant and should be determined.

3. Determining the correction factors and analyzing its impact on voltage estimation

3.1. Determining the correction factors

There are not many studies devoted to the reverse power flows of EEx. But their impact on saving energy is mainly shown by Equation 7 [17].

$$\sum E_{generate} = \int_0^{t-finish} R_{breaking} \left(I_{generated}\right)^2 dt\,, \tag{7}$$

where:

$R_{breaking}$ – the breaking resistor;

$I_{generated}$ – the generated current.

Based mainly on the energy consumed by the feeder containing EEx, this energy is calculated using a classical formula and compared with on-site measurement result at the PCC feeder nodes. Two typical feeders are presented in Figures 11 and 12.

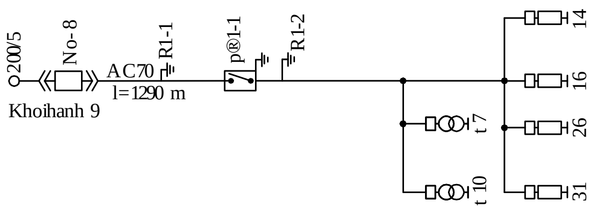

Figure 11. The feeder No 1 of the Coc Sau open-pit coal mine (14, 16, 26, 31 are EExs)

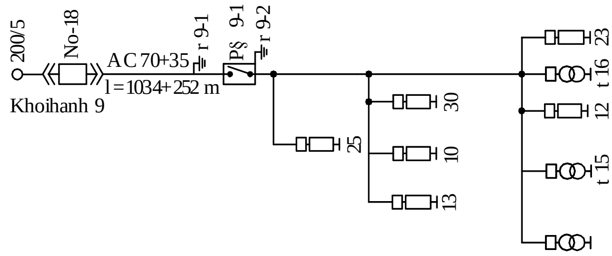

Figure 12. The feeder No 6 of the Cao Son open-pit coal mine (10, 12, 13, 23, 30 are EExs)

In the calculations, the simultaneous load factor in these 6kV feeders is 1. The EExs are assumed to delivere the power equal to their nominal power (with the main driving motor specified in Table 2). Numerous comparisons have been made, some of which are given in Table 4. The calculation with the software should be noted (mentioned in section 3.2), a series of factors corresponding to EEx numbers are given in Table 5.

Table 4. Comparison of energy consumption calculation results with on-site energy measurements at surface coal mines in Vietnam

Number of excavators	A_1 (kWh) calculated by theoretical formulas	A_2 (kWh) on-site measurement at PCC nodes of feeder	Ratio A_2/A_1
1	586233	551060	0.939
2	837992	762612	0.91
3	1411647	1224462	0.8674
4	1292532	1057292	0.818
1	1289303	1206788	0.936
2	2005337.7	1830873.3	0.913
3	2810630	2436816	0.867
4	3525644	2884329	0.8181
1	1466554	1381494	0.941
2	2270909	2061985	0.908
3	3692430	3200229	0.871
4	3922495	3207424	0.8177

Table 5. A series of modifying factors corresponding to EEx numbers at surface coal mines in Vietnam

Number of EExs	Value of factor
1	0.94
2	0.91
3	0.87
4	0.82
5	0.74
6	0.69
7	0.65

It can be seen from Table 5 which EEx number has a great impact on the power consumption of the feeder supplying power to the excavator, the ratio can be 35%. Obviously, the voltage calculation in these feeders should be estimated proportionally. The next section of this paper studies the significance of the correction factor impact.

3.2. Analyzing the impact of correction factors on voltage calculation in feeders of 6kv grids in surface mines

To analyze the impact of factors, a software is developed, which is based on Jacobian matrix transformation [22], [23]. To perform correctly voltage calculation of 6kV grid, the following assumption must be taken into account:

– shunt admittances of transmission lines can be omitted;

– all buses in the grid are load buses.

With this assumption, based on the power flow Equation presented in 8 and 9, the block diagram is shown in Figure 13.

Figure 13 shows a diagram expressing the use of modifying factors obtained from the reactive power delivered by electric-excavators. With account of these series of factors, the typical formula to verify voltage drop in a medium voltage (MV) grid has been significantly modified. Due to reactive-power compensation caused by electric excavators, all voltage drops must be multiples with a factor less than 1. In some cases, the results are greatly modified (lowered) by more than 30%. Hence, most managers and technicians responsible for the operation of MV grids must take this factor into account, which can lead to a correct understanding of the technical situation of MV grid. Moreover, the influence of these series values has a positive effect, since it shows the impact of reducing power flows transmitted in the conductor. The greater the number of excavators connected in the feeder, the greater the modifying factor (Table 5).

The power differences on 6kV feeders and buses expressed in Equations 8 and 9. The mismatch of buses in the form of Equations 8 and 9 are collected into a vector-matrix equation and expressed in Formula 10.

$$\Delta P_i = \frac{\partial P_i}{\partial \delta_2}\Delta\delta_2 + \frac{\partial P_i}{\partial \delta_3}\Delta\delta_3 + \frac{\partial P_i}{\partial \delta_4}\Delta\delta_4 + |U_2|\frac{\partial P_i}{\partial |U_2|}\frac{\Delta|U_2|}{|U_2|} + |U_3|\frac{\partial P_i}{\partial |U_3|}\frac{\Delta|U_3|}{|U_3|} + |U_4|\frac{\partial P_i}{\partial |U_4|}\frac{\Delta|U_4|}{|U_4|}; \tag{8}$$

$$\Delta Q_i = \frac{\partial Q_i}{\partial \delta_2}\Delta\delta_2 + \frac{\partial Q_i}{\partial \delta_3}\Delta\delta_3 + \frac{\partial Q_i}{\partial \delta_4}\Delta\delta_4 + |U_2|\frac{\partial Q_i}{\partial |U_2|}\frac{\Delta|U_2|}{|U_2|} + |U_3|\frac{\partial Q_i}{\partial |U_3|}\frac{\Delta|U_3|}{|U_3|} + |U_4|\frac{\partial Q_i}{\partial |U_4|}\frac{\Delta|U_4|}{|U_4|}; \tag{9}$$

$$\underbrace{\begin{bmatrix} \begin{vmatrix} \frac{\partial P_2}{\Delta\delta_2} & \cdots & \frac{\partial P_2}{\Delta\delta_4} \\ \vdots & J_{11} & \vdots \\ \frac{\partial P_4}{\Delta\delta_4} & \cdots & \frac{\partial P_2}{\Delta\delta_4} \end{vmatrix} & \begin{vmatrix} |U_2|\frac{\partial P_2}{\partial|U_2|} & \cdots & |U_4|\frac{\partial P_2}{\partial|U_4|} \\ \vdots & J_{12} & \vdots \\ |U_2|\frac{\partial P_4}{\partial|U_2|} & \cdots & |U_4|\frac{\partial P_4}{\partial|U_4|} \end{vmatrix} \\ \begin{vmatrix} \frac{\partial Q_2}{\Delta\delta_2} & \cdots & \frac{\partial Q_2}{\Delta\delta_4} \\ \vdots & J_{21} & \vdots \\ \frac{\partial Q_4}{\Delta\delta_4} & \cdots & \frac{\partial Q_2}{\Delta\delta_4} \end{vmatrix} & \begin{vmatrix} |U_2|\frac{\partial Q_2}{\partial|U_2|} & \cdots & |U_2|\frac{\partial Q_2}{\partial|U_4|} \\ \vdots & J_{22} & \vdots \\ |U_2|\frac{\partial Q_4}{\partial|U_2|} & \cdots & |U_4|\frac{\partial Q_4}{\partial|U_4|} \end{vmatrix} \end{bmatrix}}_{JACOBIAn} \begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_4 \\ \frac{|\Delta U_2|}{|U_2|} \\ \vdots \\ \underbrace{\frac{|\Delta U_4|}{|U_4|}}_{Correction} \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \vdots \\ \Delta P_4 \\ \Delta Q_2 \\ \vdots \\ \underbrace{\Delta Q_4}_{Mismatches} \end{bmatrix}. \tag{10}$$

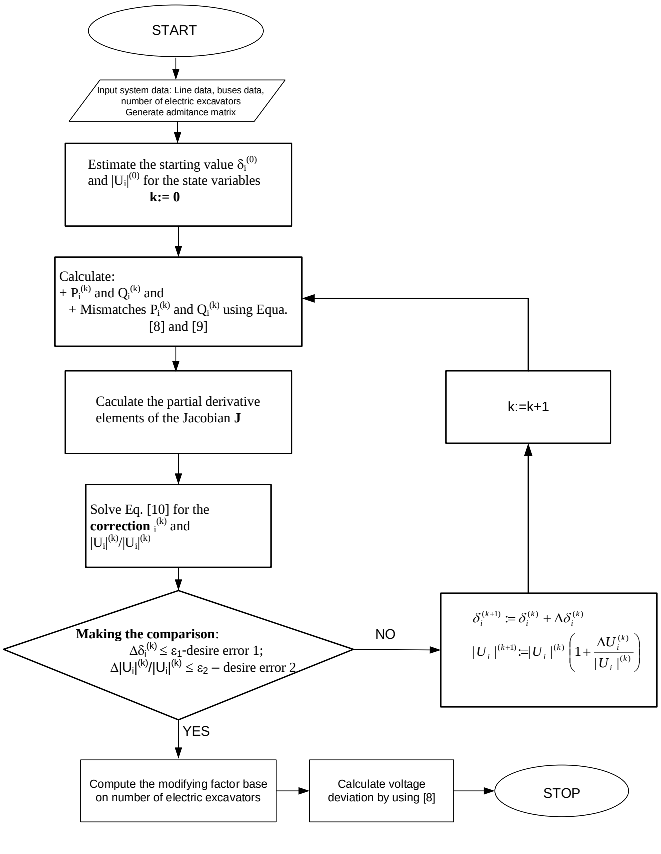

Figure 13. Block diagram presenting the calculation of the voltage drop in a 6kV grid, taken into account the EEx impact

For obtaining the impact of EEx on the voltage estimation, the factor k is included in the calculation of the Equation 11:

$$DeltaU = \frac{U_i - U_{nom}}{U_{nom}} \cdot 100\% \cdot k, \tag{11}$$

where:

U_i – voltage amplitude of bus i;

U_{nom} – rated voltage of grid.

Using a series of factors from Table 5 or software implementation, the voltage deviation calculation with and without these factors is presented in Table 6.

Table 6. Verifying the results of voltage deviation with and without taking into account the impact of using the excavators

Name	Feeder Nº	No of EEx	ΔU without k	k	ΔU with k, V
Cao Son	4	5	501.7	0.74	371.3*
	8	0	556.76	1.00	556.76
Coc Sau	2	6	669.6	0.7	468.72*
	10	1	502.23	0.94	472.09
Deo Nai	6	3	526.1	0.87	457.7
	8	3	715.56	0.87	622.53

It can be seen from the table that if the operator in surface mines ignores the good impact of electric excavator, there is some voltage quality violation in the feeders to which EEx is connected (feeder Nº 4 in Cao Son; Nº 2, 10 in Coc Sau; Nº 6 in Deo Nai). The violated voltage deviation value is 480V (permissible limit – 5% U_{rated}). If factors are used for correction, the true values of ΔU are improved, most of which are below 480V. This means that there are no technical solutions to improve voltage quality on these feeders.

4. Conclusions

By comparing simulation in MATLAB and on-site measurements, an in-depth study of the operation of electric excavators has been performed. Some facts should be taken into account following the impact of these machines on the operation of MV grids.

When working on-site, all electric excavators have a reverse power flow due to the presence of a synchronous driving motor. These power flows act as power source compensation, which reduce significantly the voltage drop in 6kV feeders in surface mines.

By re-comparing the results of theoretical calculation and on-site measurements, a series of modifying factors corresponding to the typical number of 6kV electric excavators have been determined. Depending on the number of electric excavators used in the feeder, a good impact on the field of the voltage deviation improvement has been substantiated.

The impact of using the excavators in surface-mining grids cannot be ignored. These values must be used for statistical estimation of voltage on 6kV feeders in surface mines, since the level of their impact is very high (nearly 35%) on theoretical calculations. A correct understanding of excavators as a compensating power source helps mine operators to better analyze the voltage drop calculation.

The energy saving level of the excavator, implemented in the paper, is more specific than the wide range (20% to 30%) indicated in previous studies [17], [18], [24].

Due to the fact that there are many types of various capacities used in surface mine grids in Vietnam, another detailed analysis is needed to determine the level of impact of each type or each series of capacities. Moreover, since excavators significantly reduce voltage drop, the technical voltage testing procedure needs to be improved to reflect a true understanding of grids. For this purpose, a computer program based on the diagram in Figure 13 is a good recommendation.

Acknowledgements

The authors of the paper express their special thanks to the management of the CocSau, CaoSon open-pit coal mines for their help in providing the data on the load of 6kV grids, as well as for their great support in measuring voltage in 6kV feeders.

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Виявлення факторів, що впливають на якість напруги в мережах 6 кВ, при використанні електричних екскаваторів на відкритих гірничих роботах

Л.С. Тхань, Х.В. Бун

Мета. Вивчення залежності між кількістю електроекскаваторів та їх впливом на зниження втрат напруги для встановлення факторів, які допоможуть менеджеру правильно зрозуміти ефект компенсації потужності, спричинений режимом перезбудження електричних екскаваторів.

Методика. У статті використано перетворення матриці Якобі для моделювання потоків потужності електроекскаваторів, механізмами приводу яких є переважно синхронні двигуни. Вхідними даними для моделювання є дані вимірювання на місці, що представляють зворотний потік потужності. Також надається схема та програмне забезпечення для визначення факторів, що відповідають кількості електричних екскаваторів.

Результати. Визначено ряд модифікуючих факторів, що відповідають типовій кількості електричних екскаваторів 6 кВ шляхом повторного порівняння результатів теоретичних розрахунків та вимірювань на місці. Обґрунтовано позитивний вплив на поле покращення відхилення напруги залежно від кількості електричних екскаваторів, що використовуються у живильнику. Складено таблицю перехресних довідок, яка показує співвідношення факторів, що відповідають кількості електроекскаваторів мережі 6 кВ. Розроблено також відповідне програмне забезпечення, що включає таблицю для корекції типових рівнянь для розрахунку втрат напруги.

Наукова новизна. Встановлено, що запропонований фактор обумовлений режимом перезбудження екскаваторів, що працюють як компенсаційні машини в мережі 6 кВ.

Практична значимість. Результати є корисними при розрахунку втрат напруги у мережі 6 кВ при відкритих гірничих роботах і якщо проєктний живильник містить електричні екскаватори, то слід додати модифікований коефіцієнт, щоб дати правильне уявлення про якість напруги.

Ключові слова: *електричний екскаватор, якість напруги, режим перезбудження, перетворення матриці Якобі, відкриті гірничі роботи*