

An optimization approach to determining the power of active filters

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Abstract. The coal grading plants in Vietnam extensively apply asynchronous motors with frequency control. They consume reactive power and non-sinusoidal current from the supply network. The non-sinusoidal currents and voltages lead to additional energy losses in electrical equipments, reduce their service life and cause an economic damage. Because of the low load power factor the companies with such plants pay penalties to power supply utilities. These problems can be solved by the active filters. The paper suggests an optimization algorithm to calculate the power of the active filter, which provides a load power factor corresponding to the normative documents and power quality indices corresponding to the standard requirements. The algorithm is used to calculate the power of the active filter for the coal grading plant owned by the company "Kua Ong-Vinakomin".

1 Introduction

Coal mining is one of the most important economic industries of Vietnam. Mines and quarries have coal grading plants. The manufacturing equipment of the plants is driven by asynchronous motors, primarily with frequency control. They are nonlinear loads for power supply systems and distort power quality. The harmonic factors of voltage exceed the established standards [1]. Voltages and currents contain both harmonics and interharmonics. The load power factors are lower than the value agreed by the normative documents [2].

An active filter is suggested in [3–7] to solve the problems of the load power factor, harmonics and interharmonics.

The paper presents an analysis of the power supply system of the coal grading plant, results of the tests of electric power, formulates an optimization problem and describes an algorithm to determine the power of the active filter, presents results of calculation of the power of active filter for the coal grading plant of the company “Kua Ong-Vinakomin”.

2 Characteristic of the power supply system and loads of the coal grading plant

Coal is mined in the quarry and transported to the warehouse of the coal grading plant. Fig.1 presents a scheme of the power supply of the plant. Electric power from the 22 kV substation buses of the power supply utility (node 6643) is supplied to the 0.4 kV network of the power supply system of the plant (node 4143) by the

1000 kVA step-down transformer that belongs to the coal grading plant. The distance between nodes 4143 and 45038 is 60 meters. The total length of the 0.4 kV electric network exceeds 12 km. The plant has two coal grading shops (shop No.1, shop No. 2), a shop of power and water supply, a coal warehouse. In the warehouse the excavator loads coal on the conveyer, which delivers coal to the shops for grading coal pieces by size. The manufacturing equipment of the shops is put into operation by 58 asynchronous motors with a capacity from 4 to 185 kW primarily with frequency control.

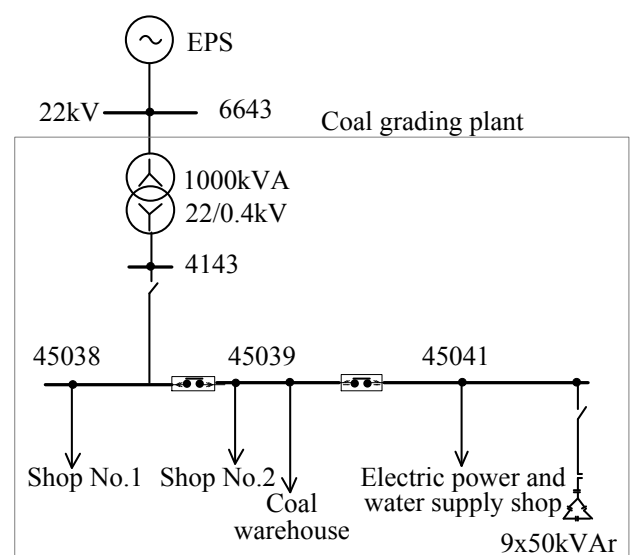


Fig. 1. Power supply system of the coal grading plant.

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To assess the quality of voltage and current in the 0.4 kV network, the following indices and norms for their values were established in [1]:

- deviation of the voltage value – $\delta U \leq \pm 5.0\%$;
- the total harmonic distortion – $K_U \leq 6.5\%$;
- the n -th harmonic factor of voltage – $K_{U(n)} \leq 3\%$;
- the n -th harmonic factor of current $K_{I(n)} \leq 12\%$.

In [2] the load power factor ($\cos\phi$) at the connection node of the plant to the supply network should comply with the condition: $\cos\phi \geq 0.85$. If this condition is not fulfilled, the company with the plant pays penalties to the power supply utility. The value of $\cos\phi$ can be low because of large reactive power consumption by the electric motors of the plant, active power losses when transmitted over the electric network and losses caused by harmonics and interharmonics. The power quality and the value of $\cos\phi$ at node 4143 were tested.

3 Results of the electrical energy tests

The tests included measurements of the indices of voltage and current quality and $\cos\phi$ by the device PQ-Box150 [8] for 24 hours with a time interval of measurements equal to 1 second.

Table 1 presents the measured values of δU , which correspond to the requirements [1]. The Table also shows the measured values of K_U and their normative values from [1]. The measured values of K_U exceed the norm more than twice. They are shown in bold type.

Table 1. Measured $\delta U, K_U, \%$.

Parameter	Phase A	Phase B	Phase C
δU_{max}	4.1	4.5	4.6
δU_{min}	-1.3	-1.7	-1.4
δU_{norm}	$\leq \pm 5.0$		
K_{Umax}	16.8	15.3	17.1
K_{Unorm}	≤ 6.5		

Table 2 presents the measured and normative values of $K_{U(n)}$ and $K_{I(n)}$ for the harmonics with the most frequent excess of the norms [1]. The measured values of $K_{I(n)}$ are not higher than the normative value.

Table 2. Measured $K_{U(n)}, K_{I(n)}, \%$.

Parameter	Harmonic						
	3	5	7	11	13	17	23
$K_{U(n)maxA}$	2.5	12.7	12.8	4.6	2.1	3.3	3.1
$K_{U(n)maxB}$	3.9	12.3	11.8	4.6	3.1	2.7	2.8
$K_{U(n)maxC}$	2.0	12.3	12.8	3.6	2.8	3.4	3.4
$K_{U(n)norm}$	≤ 3.0						
$K_{I(n)maxA}$	7.1	6.8	6.7	3.9	1.9	2.3	2.7
$K_{I(n)maxB}$	3.9	4.2	1.7	0.8	1.1	0.5	0.4
$K_{I(n)maxC}$	3.6	4.9	3.3	1.2	1.7	1.5	1.2
$K_{I(n)norm}$	≤ 12.0						

The measured values of $K_{U(m)}$ for interharmonics and the values of currents $I_{(m)max}$ of interharmonics (m – the number of the interharmonic) are given in Table 3. The

normative values for them are not determined. The measured values of $\cos\phi$ and its normative value determined in [2] are shown in Table 4. At phase B the value of $\cos\phi$ is lower than the norm.

Table 3. Measured $K_{U(m)}, \%, I_{(m)}, A$.

Parameter	Interharmonic						
	1.5	3.5	5.5	7.5	17.5	19.5	21.5
$K_{U(m)maxA}$	3.9	1.0	1.7	1.8	1.2	1.5	2.3
$K_{U(m)maxB}$	3.3	0.8	1.9	1.9	1.0	1.3	2.3
$K_{U(m)maxC}$	3.8	0.9	0.9	1.2	1.7	1.7	1.7
$I_{(m)maxA}$	16.6	6.0	5.1	4.3	7.5	8.5	9.6
$I_{(m)maxB}$	17.2	4.8	5.0	2.7	1.9	2.7	3.2
$I_{(m)maxC}$	18.0	7.3	6.4	5.3	9.2	9.7	7.5

Table 4. Measured $\cos\phi, p.u.$

Parameter	Phase A	Phase B	Phase C
$\cos\phi_{max}$	0.98	0.92	0.99
$\cos\phi_{min}$	0.89	0.72	0.89
$\cos\phi_{norm}$	≥ 0.85		

The problems caused by harmonics, interharmonics and $\cos\phi$ can be resolved using the active filter that is connected to the network in parallel to the nonlinear load.

4 Optimization problem to determine the power of the active filter

The power of the active filter is determined by the reactive power that it must generate to compensate for the reactive power of the load and the apparent power required to get rid of harmonics and interharmonics of the current at the point of its connection to the network. This can be achieved by solving an optimization problem with the objective function assumed to be the minimum active power losses in the power system network after installation of the active filter, i.e.

$$\sum_{n=1}^N \Delta P_{(n)} + \sum_{m=1.5}^M \Delta P_{(m)} = \min, \quad (1)$$

where N – the highest number of harmonic, M – the highest number of interharmonic. In this case the following constraints are to be met:

$$0.95 \leq \cos\phi \leq 1.0, \quad (2)$$

$$U_{min} \leq U_i \leq U_{max}, \quad (3)$$

$$K_{U(n)min} \leq K_{U(n)f} \leq K_{U(n)max}, \quad (4)$$

$$K_{Umin} \leq K_{Uf} \leq K_{Umax}, \quad (5)$$

$$K_{I(n)min} \leq K_{I(n)f} \leq K_{I(n)max}, \quad (6)$$

where i – the network node number; U_i – the voltage of the fundamental frequency; U_{min}, U_{max} – the normative minimum and maximum voltages of the fundamental frequency; $\cos\phi$ – the power factor at the connection

node of the plant to the supply network; $K_{U(n)f}$ – the n -th harmonic factor of voltage after installation of the active filter; $K_{U(n)min}$, $K_{U(n)max}$ – the normative maximum and minimum of the n -th harmonic factor of voltages; K_{Uf} – the total harmonic distortion after installation of the active filter; K_{Umin} , K_{Umax} – the normative maximum and minimum of the total harmonic distortion; $K_{I(n)f}$ – the n -th harmonic factor of current after installation of the active filter; $K_{I(n)min}$, $K_{I(n)max}$ – the normative maximum and minimum of the n -th harmonic factor of current. Constraint (2) was established by the company “Kua Ong-Vinakomin”.

The optimization problem consists of three subproblems:

- 1) calculation of the apparent power of the active filter to provide the normative $\cos\varphi$;
- 2) calculation of the apparent power of the active filter to eliminate current harmonics;
- 3) calculation of the apparent power of the active filter to eliminate current interharmonics.

The first subproblem is formulated in such a way: the total active power losses in the network of the fundamental frequency ($\Delta P_{(1)}$) should be minimal, i.e.

$$\Delta P_{(1)} = \min \quad (7)$$

Constraints (2) and (3) in this case should be fulfilled. If the node for active filter installation is not assigned, all nodes of the network must be considered as candidates for the active filter installation. The algorithm must consider transformer capabilities of voltage control on the lower side with the connected load. The suggested algorithm was developed based on the software “SDO” to calculate electric network modes of the fundamental frequency [9, 10]. The block-diagram of the algorithm is presented in Fig. 2.

Block 1. Input of initial information on the electric network scheme.

Block 2. Assignment of the number of regulating transformer tap k , $k = \overline{1, K}$, K – the quantity of regulating taps.

Block 3. Assignment of the reactive power value of the active filter, at the first step $Q_{AF}=0$.

Block 4. Calculation of the network mode using the software “SDO”.

Block 5. Calculation of $\cos\varphi$ at the connection node of the power supply system of the plant to the supply network based on the results of calculation by the software “SDO” as $\cos\varphi_c = P_{ij} / \sqrt{P_{ij}^2 + Q_{ij}^2}$, where “c” abbreviated from “calculated”, P_{ij} and Q_{ij} – the active and reactive powers.

Block 6. Test on fulfillment of constraint (2). If it is fulfilled, go to Block 7, otherwise go to Block 8.

Block 7. Test on fulfillment of constraint (3) at all network nodes. If it is fulfilled, then go Block 9, otherwise – to Block 8.

Block 8. Calculation of the reactive power of the active filter. The reactive power is calculated as

$$Q_{AF} = P_{ij}(tg\varphi_c - tg\varphi_d),$$

where “d” abbreviated from “desired”. The value of $tg\varphi_c$ is determined based on $\cos\varphi_c$. The value of $tg\varphi_d$ is calculated using constraint (2). As far as the admissible value of $\cos\varphi$ is within the interval

$$\cos\varphi_{min} \leq \cos\varphi \leq \cos\varphi_{max}.$$

The value of the reactive power of the active filter is also within the interval

$$Q_{min} \leq Q_{AF} \leq Q_{max}.$$

The required phase angle φ_d should be calculated using $\cos\varphi_{min}$ and $\cos\varphi_{max}$. The highest and lowest values of Q_{AF} are calculated by the expressions

$$Q_{min} = P_{ij}(tg\varphi_c - tg\varphi_{min}), \quad Q_{max} = P_{ij}(tg\varphi_c - tg\varphi_{max}).$$

Block 9. Calculation of the total active power losses in the network on the basis of results obtained by the software “SDO”.

Block 10. Comparison of the active power losses of the preceding calculation step with the losses of the current step to determine minimum losses, namely, if

$$\Delta P_{(1)} < \Delta P_{min}, \text{ then } \Delta P_{min} = \Delta P_{(1)}.$$

Block 11. Change of the number of the regulating transformer tap $k = k + 1$. If $k > K$, then go to Block 12, if the condition is not fulfilled, then go to Block 2.

Block 12. Active power losses caused by harmonics in the network should be minimal, i.e.

$$\sum_{n=2}^N \Delta P_{(n)} = \min.$$

Constraints (4) – (6) should be met in this case by elimination of the harmonics of current with the help of the active filter at the node of filter connection. The apparent harmonic power is calculated in accordance with [13] as $S_{n\Sigma} = \sqrt{P_n^2 + Q_n^2}$, where

$$P_n = \sum_{n=2}^N U_n I_n \cos\varphi_n, \quad Q_n = \sum_{n=2}^N U_n I_n \sin\varphi_n$$

were calculated by the measured voltages U_n , currents I_n and phase angle φ_n .

Block 13. The active power losses caused by the interharmonics in the network should be minimal, i.e.

$$\sum_{m=1.5}^M \Delta P_{(m)} = \min.$$

For this purpose the interharmonics of current should be eliminated by the active filter at the node of filter connection. The apparent power of interharmonics is calculated as $S_{m\Sigma} = \sum_{m=1.5}^M U_m I_m$ by the measured voltages U_m and currents I_m .

Block 14. Calculation of the apparent power of the active filter as a sum of three powers:

$$S_{AF} = S_{Q_{AF}} + S_{n\Sigma} + S_{m\Sigma}.$$

Block 15. Output of calculation results.

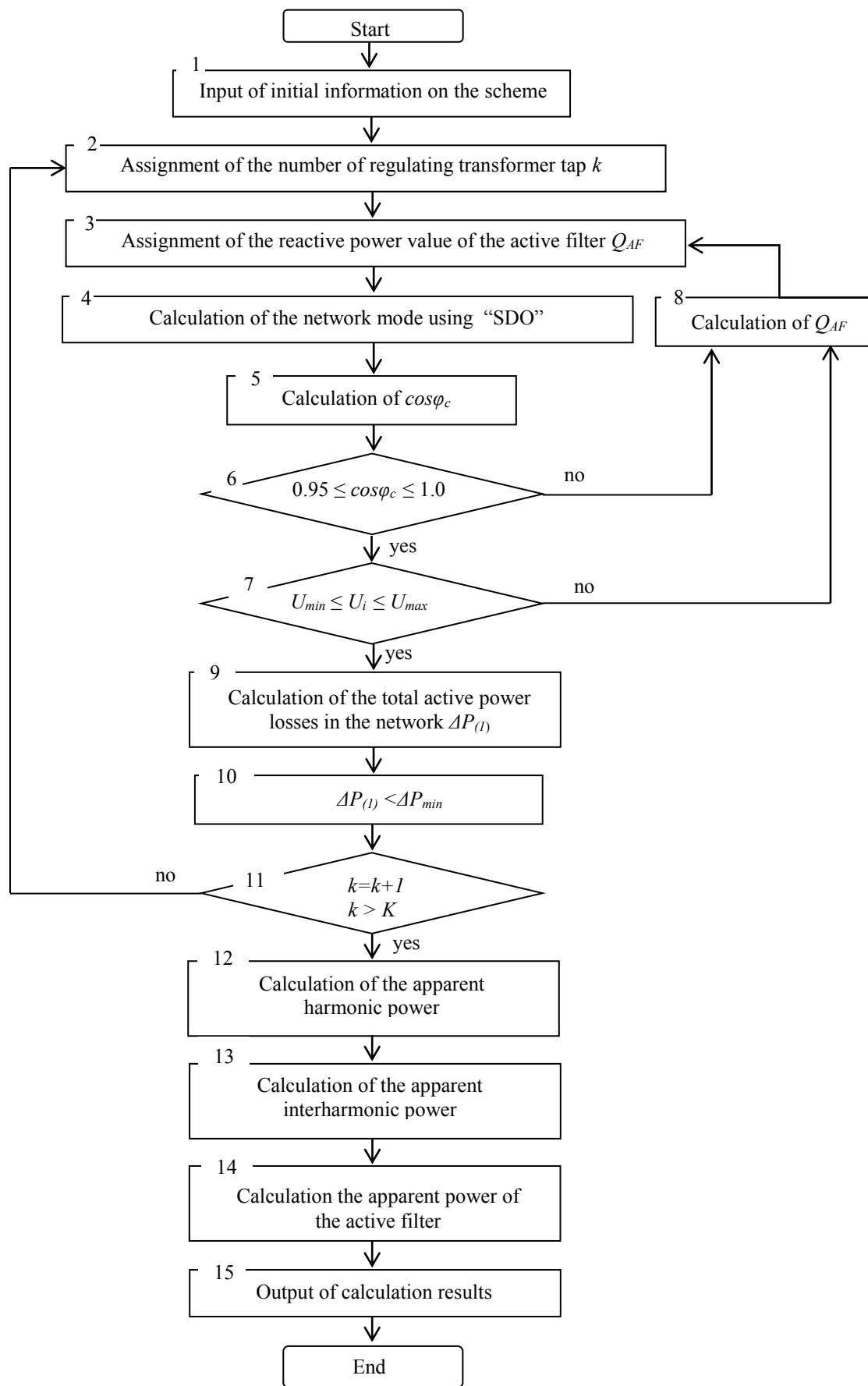


Fig. 2. Block-diagram of the algorithm to determine the power of the active filter.

5 Determination of the apparent power of the active filter for the coal grading plant of the company “Kua Ong-Vinakomin”

The management company of the coal grading plant has chosen node 45038 for installation of an active filter in power supply system (Fig. 1). The transformer supplying electric energy to the power supply system of the plant has 5 regulating taps. They make it possible to have at node 4143 the following voltages: 0.38 kV, 0.39 kV, 0.4 kV, 0.41 kV, and 0.42 kV. The calculation results of the software show that if the voltages at node 4143 change from 0.38 kV to 0.42 kV, at 57 network nodes of 0.4 kV the voltages range from 0.36 kV to 0.39 kV. Hence, the requirements of [2] are not fulfilled. The load power factor at node 4143 in this case takes the values from 0.88 kV to 0.99 kV, which answers incompletely to the requirements of the company. Thus, generation of reactive power can increase voltage values at the system nodes and the load power factor at node 4143.

The software “SDO” in accordance with the proposed algorithm was applied to calculate the reactive power value of the active filter. The calculation results are presented in Tables 5 and 6. The lowest active power losses in the network equal to 110-120 kW are observed with the regulating tap of the 0.42 kV transformer and the values of reactive power of the active filter of 410-580 kVAr. And all the conditions on voltage values at the network nodes and at node 4143 are met. Harmonic powers were calculated based on the measured parameters and shown in Table 7. The active filter to

eliminate harmonics of current must be no less than 17 kVA in each phase.

Table 5. Q_{AF} and $\Delta P_{(I)\Sigma}$ calculated by the algorithm.

U_{4143}, kV	$Q_{AF}, kVAr$	$\Delta P_{(I)\Sigma}, kWt$
0.38	300–350	297–311
0.39	445–480	290–294
0.40	250–330	192–297
0.41	245–450	134–157
0.42	410–580	110–120

Table 6. U_{min} , U_{max} , and $\cos\varphi_{4143}$ calculated by the algorithm.

U_{4143}, kV	$\cos\varphi_{4143}$	U_{min}, kV	U_{max}, kV
0.38	0.95–0.98	0.37	0.39
0.39	0.96–0.97	0.38	0.39
0.40	0.99–1.00	0.38	0.39
0.41	0.98–1.00	0.38	0.41
0.42	0.97–1.00	0.38	0.41

Table 7. Active, reactive and apparent powers of harmonics.

Parameter	Phase A	Phase B	Phase C
P_n, kWt	8.9	9.6	7.2
$Q_n, kVAr$	11.0	10.3	14.4
S_n, kVA	14.1	14.1	16.1

Table 8 presents the values of phase powers of interharmonics and the total powers of three phases that were calculated by the measured parameters. The apparent power of interharmonics at three phases accounts for 313.7 VA.

Table 8. Apparent powers of interharmonics.

S_m, VA	Interharmonic										
	1.5	3.5	5.5	7.5	9.5	11.5	13.5	15.5	17.5	19.5	21.5
Phase A	16.6	6.0	5.1	4.3	3.9	5.1	5.1	4.5	7.5	8.5	9.6
Phase B	17.2	4.8	5.0	2.7	2.5	3.7	2.2	1.7	1.9	2.7	3.2
Phase C	18.0	7.3	6.4	5.3	5.1	5.0	5.2	4.8	9.2	9.7	7.5
$S_{m\Sigma A,B,C}$	51.8	18.1	16.5	12.3	11.5	13.8	12.5	11.0	18.6	20.9	20.3
S_m, VA	Interharmonic										
	23.5	25.5	27.5	29.5	31.5	33.5	35.5	37.5	39.5	41.5	43.5
Phase A	13.1	12.5	7.0	7.5	5.4	4.7	3.3	2.4	2.8	1.8	1.3
Phase B	3.0	2.7	1.9	1.4	1.1	0.9	0.9	0.7	0.6	0.5	0.5
Phase C	5.7	6.5	3.8	3.6	2.0	1.8	1.5	2.0	1.6	1.0	0.9
$S_{m\Sigma A,B,C}$	21.8	21.7	12.7	12.5	8.5	7.4	5.7	5.1	5.0	3.3	2.7

6 Conclusions

The measurements have shown that the load current contains harmonics and interharmonics, the indices $K_{U(n)}$ and K_U exceed the normative values, and $\cos\varphi$ is lower than the norm.

The total harmonic distortion reduction and the load power factor increase can be achieved by installation of the active filter. The power of the active filter was determined by the developed optimization algorithm and using the results of measurements of mode parameters of network.

The power of the active filter was determined for the coal grading plant of the company “Kua Ong-Vinakomin”.

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