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An Optimization Algorithm to Determine Apparent Power of Active Filter

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***Abstract* — The coal grading plants in Viet Nam extensively apply induction motors. Induction motors consume active and reactive power from the power supply systems. The reactive power flowing through the electrical network creates active power losses. The reactive power received from power utilities reduces the load power factor at the node where coal sorting plants are connected to the supply network. Frequency-controlled induction motors introduce distortions into the electrical network because they are electrical equipment with a nonlinear current-voltage characteristic. Non-sinusoidal current and voltage cause additional losses of active power in the electrical network and electrical equipment, thereby shortening its service life, reducing the reliability of operation, and causing economic damage. Active filters can solve these problems. The paper proposes an optimization algorithm for determining the apparent power of the active filter, which provides the load power factor and power quality indices corresponding to the regulatory documents. The algorithm is used to calculate the apparent power of the active filter for the coal grading plant owned by the Vietnamese company "Cua Ong-Vinacomin."**

***Index Terms*—Active filter, algorithm, harmonic, load power factor, power quality index.**

I. INTRODUCTION

Coal mining is one of the most important economic industries of Viet Nam. Mines and quarries have coal grading plants. Induction motors, primarily with frequency control, drive the manufacturing equipment of the plants. They are nonlinear loads for the power supply system and distort power quality. The harmonic factors of voltage exceed the established standards [1]. Voltages and currents contain both harmonics and interharmonics [2]. The load power factors are lower than the value established by the normative documents [3].

In [4-7], the authors determine the active filter power to reduce the voltage and current harmonics in the electrical network. The power of the active filter is not only determined by the power of the harmonics. The use of the active filter is not confined only by the need to reduce harmonic values. Many consumers have additional economic losses because their electrical equipment receives reactive power from the supply network. In this context, the load power factor at the node connecting the power supply system of consumers to the supply network is lower than the standard value established for consumers. In [8-11], the authors use the active filter to compensate for reactive power and reduce harmonics. The authors of these papers do not consider active power losses due to reactive power transmission through the electrical network. Consumers have to pay for these losses and thus face additional economic damage. In [12-15], the authors determine the power of active filter to compensate for reactive power and reduce the values of harmonics, thereby providing the minimum losses of active power during the transmission of reactive power and the flow of harmonic currents in the electrical network of the power supply system.

The paper is concerned with an analysis of the power supply system of the coal grading plant, and results of the power quality tests. It formulates an optimization

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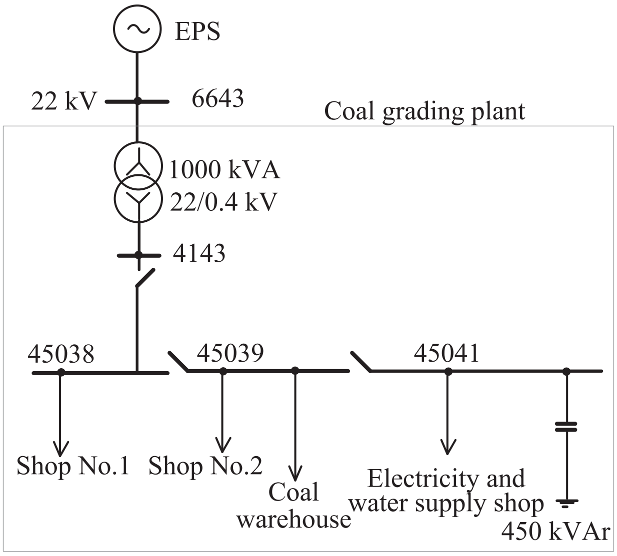


Fig. 1. Power supply system of the coal grading plant.

problem, describes an algorithm to determine the apparent power of the active filter, and presents specially designed software and results of the active filter apparent power calculation for the coal grading plant of the company "Cua Ong-Vinacomin."

II. CHARACTERISTIC OF THE POWER SUPPLY SYSTEM AND LOADS OF THE COAL GRADING PLANT

Fig.1 presents a scheme of the power supply system of the coal grading plant.

Electrical 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 coal grading plant (node 4143) by the 1000 kVA step-down transformer that belongs to the plant. The distance between nodes 4143 and 45038 is 60 meters. The total length of the 0.4 kV electrical network exceeds 12 km. The plant has two coal grading shops (shop No.1, shop No. 2), a shop of electricity and water supply, and a coal warehouse. Coal is mined in the quarry and transported to the warehouse of the coal grading plant. In the warehouse, the excavator unloads coal on the conveyor. The conveyor delivers coal to the shops for grading it by size. Fifty-eight induction motors with a capacity of 4 to 185 kW put the technological equipment of the shops into operation.

The following indices and norms for their values were established in [1] to assess voltage and current values in the 0.4 kV network:

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

In [2], the load power factor (cos φ) at the connection node of the plant to the supply network should meet the condition cos φ ≥0.85. If this condition is not fulfilled, the company, owner of the plant, pays penalties to the power supply utility. The value of cos φ can be low because of large reactive power consumption by the electrical motors of the plant, active power losses when transmitted over the electrical network, and losses caused by harmonics and interharmonics. Power quality indices and the value of cos φ at node 4143 were tested.

Table 1. Measured δU, 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
$\lvert\delta U_{norm}\rvert$		≤ 5.0	
K_{Umax}	**16.8**	**15.3**	**17.1**
K_{Unorm}		≤ 6.5	

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

Parameter	Harmonic						
	3	5	7	11	13	17	23
$K_{U(h)maxA}$	2.5	**12.7**	**12.8**	**4.6**	2.1	**3.3**	**3.1**
$K_{U(h)maxB}$	**3.9**	**12.3**	**11.8**	**4.6**	**3.1**	2.7	2.8
$K_{U(h)maxC}$	2.0	**12.3**	**12.8**	**3.6**	2.8	**3.4**	**3.4**
$K_{U(h)norm}$				≤ 3.0			
$K_{I(h)maxA}$	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
$K_{I(h)maxC}$	3.6	4.9	3.3	1.2	1.7	1.5	1.2
$K_{I(h)norm}$				≤ 12.0			

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 φ, p.u.

Parameter	Phase A	Phase B	Phase C
cos φ_{max}	0.98	0.92	0.99
cos φ_{min}	0.89	**0.72**	0.89
cos φ_{norm}		≥0.85	

III. RESULTS OF THE ELECTRICAL ENERGY TESTS

The tests included 24-hour measurements of the voltage and current quality indices and cos φ by the device PQ-Box150 [16] with a time interval of measurements equal to 1 second.

Table 1 presents the measured values of δU, which meet 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 2 presents the measured and normative values of $K_{U(h)}$ and $K_{I(h)}$ for the harmonics that exceed the norms

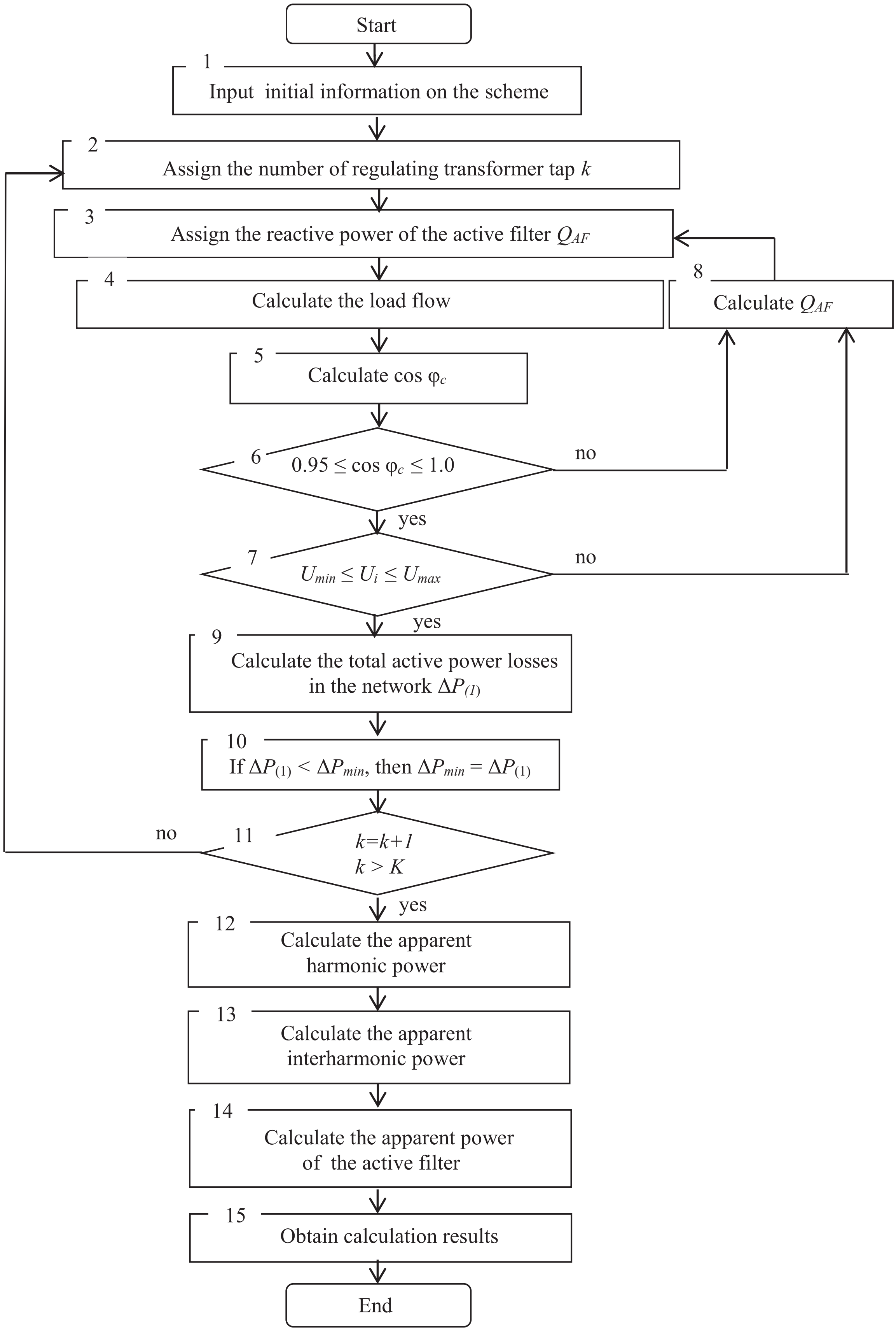


Fig. 2. Block-diagram of the algorithm to determine the power of the active filter.

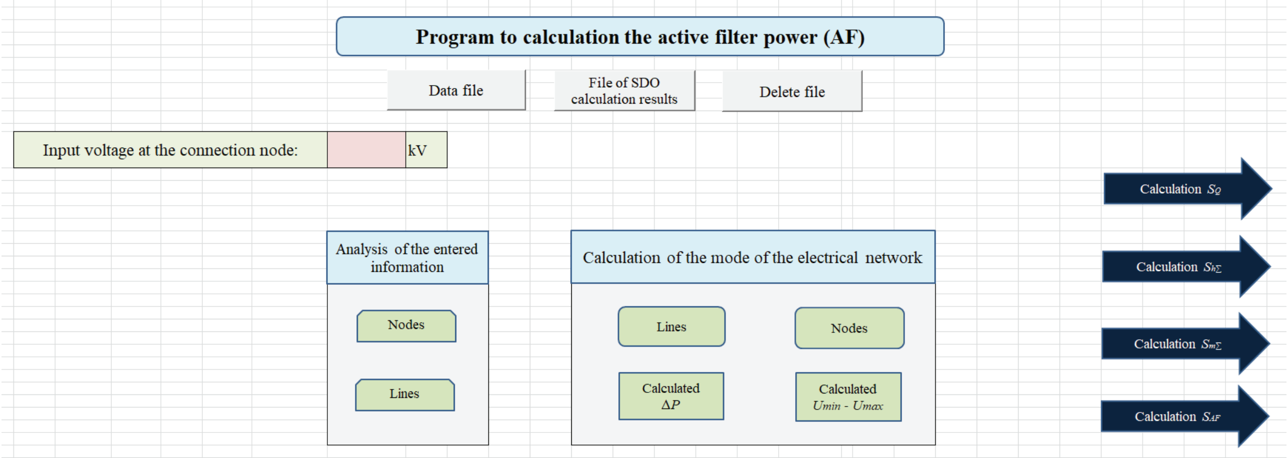


Fig. 3. Sheet 1 of the program.

most frequently [1]. The measured values of $K_{I(h)}$ are not higher than the normative value.

The measured values of $K_{U(m)}$ for some interharmonics and the values of currents $I_{(m)max}$ of these 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 φ and its normative value determined in [3] are shown in Table 4. At phase B, the value of cos φ is lower than the norm.

The problems caused by harmonics, interharmonics, and cos φ can be resolved using a shunt active filter connected to the network in parallel to the nonlinear load [7-15, 17-20].

IV. OPTIMIZATION PROBLEM TO DETERMINE THE POWER OF THE ACTIVE FILTER

The power of the active filter is determined by the reactive power to be generated to compensate for the reactive power of load and apparent power required to get rid of harmonics and interharmonics of the current at the point of the filter 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.,

$$\sum_{h=1}^{H}\Delta P_{(h)}+\sum_{m=1}^{M}\Delta P_{(m+\frac{1}{2})}=\min\ , \qquad (1)$$

where H is the highest number of the harmonic, $(M-1/2)$ is the highest number of interharmonic. In this case, the following constraints are to be met

$$0.95\le\cos\varphi\le1.0, \qquad (2)$$

$$U_{min}\le U_i\le U_{max}, \qquad (3)$$

$$K_{U(h)min}\le K_{U(h)\,f}\le K_{U(h)max}, \qquad (4)$$

$$K_{Umin}\le K_{U\,f}\le K_{Umax}, \qquad (5)$$

$$K_{I(h)min}\le K_{I(h)f}\le K_{I(h)max}, \qquad (6)$$

where i is the network node number; U_i is the voltage of the fundamental frequency; U_{min}, U_{max} are the normative minimum and maximum voltages of the fundamental frequency; cos φ is the load power factor at the node connecting the plant to the supply network; $K_{U(h)\,f}$ is the h-th harmonic factor of voltage after installation of the active filter; $K_{U(h)min}$, $K_{U(h)max}$ are the normative maximum and minimum of the h-th harmonic factor of voltages; K_{Uf} is the total harmonic distortion after installation of the active filter; K_{Umin}, K_{Umax} are the normative maximum and minimum of the total harmonic distortion; $K_{I(h)f}$ is the h-th harmonic factor of current after installation of the active filter; $K_{I(h)min}$, $K_{I(h)max}$ are the normative maximum and minimum of the h-th harmonic factor of current. Constraint (2) was established by the company “Cua Ong-Vinacomin”.

The optimization problem consists of three subproblems:

1. calculation of the apparent power of the active filter to provide the normative cos φ;
2. calculation of the apparent power of the active filter to eliminate current harmonics;

Table 5. Q_{AF} and $\Delta P_{(1)\Sigma}$ calculated by the algorithm.

U_{4143}, kV	Q_{AF}, kVAr	$\Delta P_{(1)\Sigma}$, kW
0.38	350	297
0.39	480	290
0.40	330	192
0.41	450	134
0.42	580	110

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

U_{4143}, kV	cos ϕ_{4143}, p.u.	U_{min}, kV	U_{max}, kV
0.38	0.98	0.38	0.39
0.39	0.97	0.38	0.39
0.40	1.00	0.38	0.39
0.41	0.99	0.38	0.41
0.42	1.00	0.38	0.41

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

Parameter	Phase A	Phase B	Phase C
P_h, kW	8.9	6.9	7.2
Q_h, kVAr	11.0	7.3	14.4
S_h, kVA	14.1	10.1	16.1

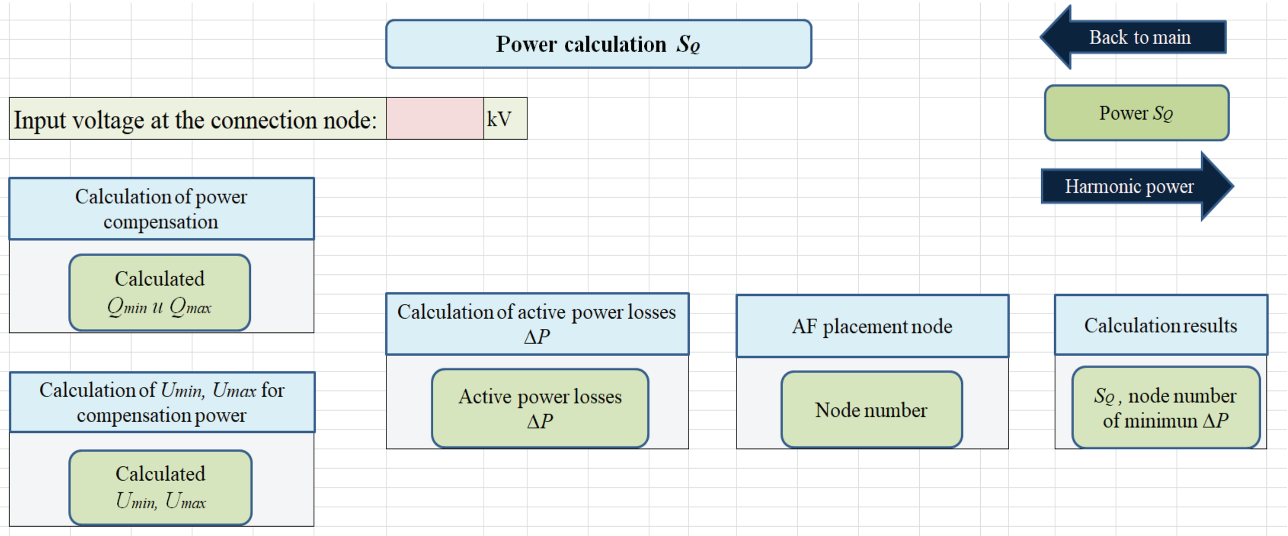


Fig. 4. Sheet 2 of the program.

3. calculation of the apparent power of the active harmonic filter to eliminate current interharmonics.

The first subproblem is formulated as follows: minimize the total active power losses in the network at the fundamental frequency, i.e.

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

In this case, constraints (2) and (3) should be fulfilled. If a node for active filter installation is not assigned, all nodes of the network must be considered as candidates for 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 the fundamental frequency load flow [21-22]. The block diagram of the algorithm is presented in Fig. 2.

Block 1. Input initial information on the electrical network scheme.

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

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

Block 4. Calculate the load flow.

Block 5. Calculate cos φ at the connection node of the power supply system of the plant to the supply network based on the results of calculation using the expression $\cos\varphi_c = P_{ij}/\sqrt{P_{ij}^2 + Q_{ij}^2}$, where “$c$” is an abbreviation of "calculated," P_{ij} and Q_{ij} are the active and reactive powers, i, j are the network node numbers.

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

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

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

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

where “d” is an abbreviation of “desired." The value of $\mathrm{tg}\,\varphi_c$ is determined based on $\cos\varphi_c$. The value of $\mathrm{tg}\,\varphi_d$ is calculated using constraint (2). Since the feasible value of cos φ is within the interval

$$\cos\varphi_{min} \le \cos\varphi \le \cos\varphi_{max},$$

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

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

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

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

Block 9. Calculate the total active power losses in the network based on the load flow calculation.

Block 10. Compare 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 the number of the transformer tap $k = k + 1$. If $k > K$, then go to Block 12, if the condition is not fulfilled, go to Block 2.

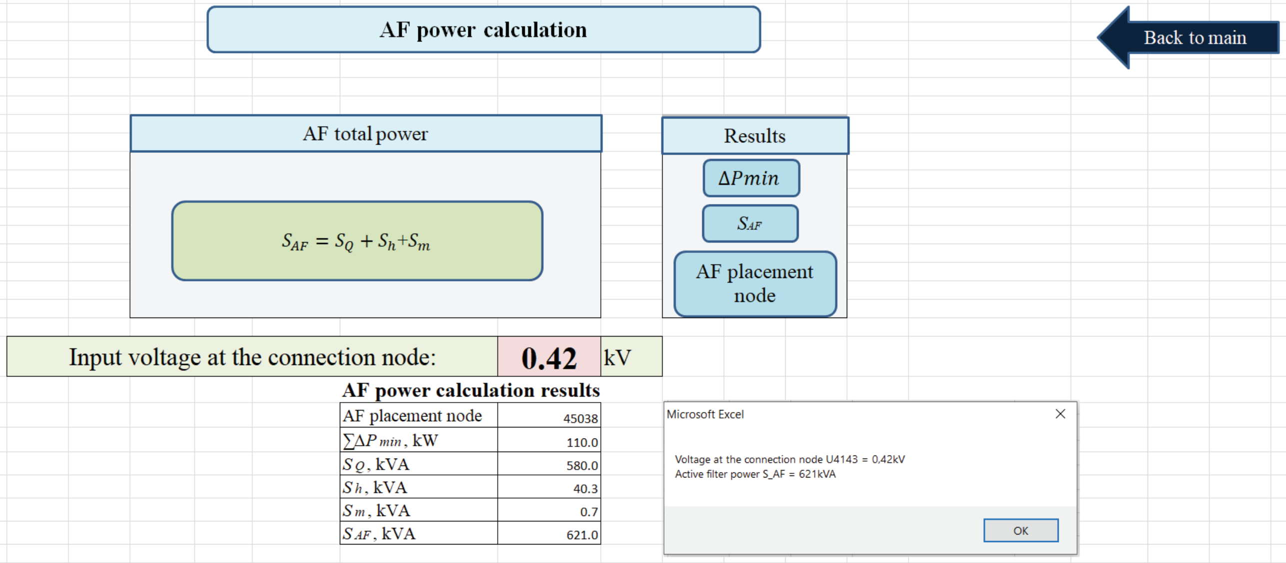
Block 12. Minimize the active power losses caused by harmonics in the network, i.e., $\sum_{h=2}^{H} \Delta P_{(h)} = \min$.

In this case, constraints (4)–(6) should be met by eliminating the harmonics of current with the help of the active filter at the node of filter connection. The apparent harmonic power is calculated as $S_{h\text{ó}} = \sqrt{P_h^2 + Q_h^2}$ [23], where

$$P_h = \sum_{h=2}^{H} U_h I_h \cos\varphi_h\,,$$

$$Q_h = \sum_{h=2}^{H} U_h I_h \sin\varphi_h$$

were calculated by the measured voltages U_h, currents I_h and phase angle φ_h.



Input voltage at the connection node: **0.42** kV

AF power calculation results

AF placement node	45038
$\sum \Delta P_{min}$, kW	110.0
S_Q, kVA	580.0
S_h, kVA	40.3
S_m, kVA	0.7
S_{AF}, kVA	621.0

Microsoft Excel

Voltage at the connection node U4143 = 0,42kV
Active filter power S_AF = 621kVA

OK

Fig. 5. Sheet 5 of the program.

Block 13. Minimize the active power losses caused by the interharmonics in the network, i.e.,

$$\sum_{m=1}^{M} \Delta P_{\left(m+\frac{1}{2}\right)} = \min .$$

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 $S_{m\Sigma} = \sum_{m=1}^{M} U_{m+1/2} I_{m+1/2}$ by the measured voltages U_m and currents I_m.

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

$$S_{AF} = S_{QAF} + S_{h\Sigma} + S_{m\Sigma}.$$

Block 15. Obtain calculation results.

V. THE COMPUTER PROGRAM TO CALCULATE THE ACTIVE FILTER POWER

The computer program [24] was developed based on the algorithm built to determine the active filter power presented in Fig. 2. It is written in MS Excel and the programming environment Visual Basic for Windows applications. The program is designed to determine the apparent active filter power to compensate for the reactive load power for improving the power factor, and eliminating harmonics and interharmonics. The program makes it possible to determine a network node for placing an active filter.

The computer program component of the mentioned software "The stationary feasible optimal condition" (the software “SDO”) is applied to calculate the value of power to be generated by the active filter for compensation for the reactive load power and to determine the network node for installation of the active filter [20-21]. This software is intended for the calculation of the steady-state conditions in electrical networks. It implements algorithms for calculation of feasible and optimal conditions in terms of the active and reactive power losses in the electrical networks with different voltage levels, including the steady-state unbalanced conditions of low-voltage distribution networks.

The program for calculation of active load power filter consists of five MS Excel sheets: sheet 1 is "Primary”, sheet 2 is “Power Q_{AF}”, sheet 3 is "Harmonics power S_h”, sheet 4 is “Interharmonics power S_m”, sheet 5 is “Power S_{AF}”. Figure 3 presents the first sheet as an example. The fundamental frequency load flow and the comparative evaluation of cos φ and U_k values, which were measured and calculated using the software “SDO” at the node connecting the power supply system of the plant to the supply network, were calculated using the commands of the first sheet. Comparison of the calculated parameters with the results of measurements and their close values confirms that modeling of the electrical network for calculation of the reactive power value was correct.

The reactive power value consumed by the load generated by the active filter is calculated in sheet 2 (Fig. 4). The electrical network node for the installation of the active filter is identified through calculation. If the node is determined correctly, the active power losses in the network elements will be minimal.

Table 8. Apparent powers of interharmonics.

S_m,VA	Interharmonic					
	1.5	3.5	5.5	17.5	19.5	11.5
Phase A	16.6	6.0	5.1	7.5	8.5	5.1
Phase B	17.2	4.8	5.0	1.9	2.7	3.7
Phase C	18.0	7.3	6.4	9.2	9.7	5.0
$S_{m\Sigma A,B,C}$	51.8	18.1	16.5	18.6	20.9	13.8
S_m,VA	Interharmonic					
	13.5	21.5	23.5	25.5	27.5	29.5
Phase A	5.1	9.6	13.1	12.5	7.0	7.5
Phase B	2.2	3.2	3.0	2.7	1.9	1.4
Phase C	5.2	7.5	5.7	6.5	3.8	3.6
$S_{m\Sigma A,B,C}$	12.5	20.3	21.8	21.7	12.7	12.5

The apparent power values of harmonics and interharmonics to be eliminated by the active filter are calculated in sheets 3 and 4. The powers are calculated by the results of measurements of harmonic load flow parameters and power quality indices at the electrical network node chosen for the active filter installation.

The apparent power of the active filter is calculated in sheet 5 of the program. Sheet 5 with the Table of the calculation results is presented in Fig. 5. The Table indicates the number of the network node for installation of the active filter, the value of the minimum active power losses, the reactive power of the fundamental frequency, the harmonic power, the interharmonic power, and the apparent power of the active filter.

VI. Determination of the apparent power of the active filter harmonics for the coal grading plant of the company "Cua Ong-Vinacomin"

The management company of the coal grading plant has chosen node 45038 for the installation of an active filter in the power supply system (Fig. 1). The transformer supplying electrical power to the power supply system of the plant has five taps. They make it possible to have the voltages of 0.38 kV, 0.39 kV, 0.4 kV, 0.41 kV, and 0.42 kV at node 4143. The calculation results show that if the voltage at node 4143 changes 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 [3] are not fulfilled. In this case, the load power factor at node 4143 takes the values from 0.88 to 0.99, which meets partially the company requirements. Thus, the generation of reactive power can increase the voltage at the system nodes and the load power factor at node 4143.

The computer program for calculating the active filter power following the proposed algorithm was applied to calculate the reactive power value of the active filter. The intermediate calculation results are presented in Tables 5 and 6.

The lowest active power losses in the network equal to 110 kW are observed with the tap of the 0.42 kV transformer and the reactive power of the active filter of 580 kVAr. All the voltage conditions at the network nodes and node 4143 are met.

Harmonic powers were calculated based on measured parameters and are shown in Table 7. The active filter must have no less than 16 kVA at each phase to eliminate harmonic currents. The total apparent power of harmonics in three phases is 40.3 kVA.

Table 8 presents the values of phase apparent power of some interharmonics and the total apparent powers of three phases, which were calculated by measured parameters. The total apparent power of interharmonics of three phases is 0.7 kVA, which is less than 1% of the harmonic power.

Figure 5 demonstrates the calculation results presented in the fifth sheet of the computer program. The Figure shows that at node 45038 of the active filter connection, the active power losses in the electrical network of the coal grading plant will be minimal and equal to 110 kW with the transformer tap of 0.42 kV and the apparent power of the active filter of 621.1 kVA.

VII. Conclusion

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 φ is lower than the norm.

Reduction in total harmonic distortion and increase in load power factor can be achieved with an active filter installed. The power of the active filter was determined using the developed optimization algorithm and measurements of load flow parameters.

The active filter power was determined for the coal grading plant of the company "Cua Ong-Vinacomin."

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