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.

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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 $\varphi$) at the connection node of the plant to the supply network should meet the condition cos $\varphi \geq 0.85$. If this condition is not fulfilled, the company, owner of the plant, pays penalties to the power supply utility. The value of cos $\varphi$ 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 $\varphi$ at node 4143 were tested.

III. RESULTS OF THE ELECTRICAL ENERGY TESTS

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

Table 1 presents the measured values of $\delta U$, 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.

1. Input initial information on the scheme
2. Assign the number of regulating transformer tap \( k \)
3. Assign the reactive power of the active filter \( Q_{AF} \)
4. Calculate the load flow
5. Calculate \( \cos \phi_c \)
6. \( 0.95 \leq \cos \phi_c \leq 1.0 \)
7. \( U_{\text{min}} \leq U_i \leq U_{\text{max}} \)
8. Calculate \( Q_{AF} \)
9. Calculate the total active power losses in the network \( \Delta P_{(1)} \)
10. If \( \Delta P_{(1)} < \Delta P_{\text{min}} \), then \( \Delta P_{\text{min}} = \Delta P_{(1)} \)
11. \( k = k + 1 \)
   \( k > K \)
12. Calculate the apparent harmonic power
13. Calculate the apparent interharmonic power
14. Calculate the apparent power of the active filter
15. Obtain calculation results

End
the fundamental frequency; \( K_{U_{\text{min}}} \) is the minimum of the harmonic, \( K_{U_{\text{max}}} \) is the maximum of the harmonic after installation of the active filter, i.e.,

\[
\sum_{h=1}^{H} \Delta P_{(h)} + \sum_{m=1}^{M} \Delta P_{(m/2)} = \min, \tag{1}
\]

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

\[
0.95 \leq \cos \phi \leq 1.0, \tag{2}
\]

\[
U_{\min} \leq U_{i} \leq U_{\max}, \tag{3}
\]

\[
K_{i}^{(h)\min} \leq K_{i}^{(h)\max} \leq K_{i}^{(h)\max}, \tag{4}
\]

\[
K_{i}^{(\min)} \leq K_{i}^{(\max)} \leq K_{i}^{(\max)}, \tag{5}
\]

\[
K_{i}^{(\min)} \leq K_{i}^{(\max)} \leq K_{i}^{(\max)}, \tag{6}
\]

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; \( \cos \phi \) is the load power factor at the node connecting the plant to the supply network; \( K_{i}^{(h)\max} \) is the \( h \)-th harmonic factor of voltage after installation of the active filter; \( K_{i}^{(h)\min} \) are the normative minimum and maximum of the \( h \)-th harmonic factor of voltages; \( K_{i}^{(h)} \) is the total harmonic distortion after installation of the active filter; \( K_{i}^{(h)\min}, K_{i}^{(h)\max} \) are the normative minimum and maximum of the total harmonic distortion; \( K_{i}^{(h)\max} \) 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 minimum and maximum 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 \( \cos \phi \);
2. calculation of the apparent power of the active filter to eliminate current harmonics.

### Table 5. \( U_{\text{max}}, K_{U} \) and \( \Delta P_{(h)} \) calculated by the algorithm.

<table>
<thead>
<tr>
<th>( U_{\text{max}}, \text{kV} )</th>
<th>( Q_{\text{ar}}, \text{kVAr} )</th>
<th>( \Delta P_{(h)}, \text{kW} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>350</td>
<td>297</td>
</tr>
<tr>
<td>0.39</td>
<td>480</td>
<td>290</td>
</tr>
<tr>
<td>0.40</td>
<td>330</td>
<td>192</td>
</tr>
<tr>
<td>0.41</td>
<td>450</td>
<td>134</td>
</tr>
<tr>
<td>0.42</td>
<td>580</td>
<td>110</td>
</tr>
</tbody>
</table>

### Table 6. \( U_{\min}, U_{\max}, \text{and } \cos \phi \) calculated by the algorithm.

<table>
<thead>
<tr>
<th>( U_{\text{min}}, \text{kV} )</th>
<th>( \cos \phi ), p.u.</th>
<th>( U_{\text{max}}, \text{kV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>0.98</td>
<td>0.38</td>
</tr>
<tr>
<td>0.39</td>
<td>0.97</td>
<td>0.38</td>
</tr>
<tr>
<td>0.40</td>
<td>1.00</td>
<td>0.38</td>
</tr>
<tr>
<td>0.41</td>
<td>0.99</td>
<td>0.38</td>
</tr>
<tr>
<td>0.42</td>
<td>1.00</td>
<td>0.38</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{r}}, \text{kW} )</td>
<td>8.9</td>
<td>6.9</td>
<td>7.2</td>
</tr>
<tr>
<td>( Q_{\text{ar}}, \text{kVAr} )</td>
<td>11.0</td>
<td>7.3</td>
<td>14.4</td>
</tr>
<tr>
<td>( S_{\text{a}}, \text{kVA} )</td>
<td>14.1</td>
<td>10.1</td>
<td>16.1</td>
</tr>
</tbody>
</table>
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.

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

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 $k, k = 1, K$, $K$ 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 $\cos \varphi$ 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 $Q_{AF} = P_{ij} (\tan \varphi_c - \tan \varphi_d)$, where “d” is an abbreviation of “desired.” The value of $\tan \varphi_c$ is determined based on $\cos \varphi_c$. The value of $\tan \varphi_d$ is calculated using constraint (2). Since the feasible 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 $\varphi_d$ should be calculated using $\cos \varphi_{\min}$ and $\cos \varphi_{\max}$. The highest and lowest values of $Q_{AF}$ are calculated by the expressions

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

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

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

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

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 $S_{oh} = \sqrt{P_h^2 + Q_h^2}$ [23], where

$$P_h = \sum_{k=2}^{\infty} U_k I_k \cos \varphi_h,$$
$$Q_h = \sum_{k=2}^{\infty} U_k I_k \sin \varphi_h,$$
were calculated by the measured voltages $U_k$, currents $I_k$ and phase angle $\varphi_h$. 

Fig. 4. Sheet 2 of the program.
Block 13. Minimize the active power losses caused by the interharmonics in the network, i.e.,

\[ \sum_{n=1}^{M} \Delta P_{n+1} = \min \]

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 \( S_{m} = \sum_{n=1}^{N} U_{n+1/2} I_{n+1/2} \) by the measured voltages \( U_{n} \) and currents \( I_{n} \).

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

\[ S_{AF} = S_{QAF} + S_{h} + S_{m} \]

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 \( \phi \) 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>
<thead>
<tr>
<th>Interharmonic</th>
<th>1.5</th>
<th>3.5</th>
<th>5.5</th>
<th>17.5</th>
<th>19.5</th>
<th>11.5</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase A</td>
<td>16.6</td>
<td>6.0</td>
<td>5.1</td>
<td>7.5</td>
<td>8.5</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>Phase B</td>
<td>17.2</td>
<td>4.8</td>
<td>5.0</td>
<td>1.9</td>
<td>2.7</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Phase C</td>
<td>18.0</td>
<td>7.3</td>
<td>6.4</td>
<td>9.2</td>
<td>9.7</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>( S_{h,AF} )</td>
<td>51.8</td>
<td>18.1</td>
<td>16.5</td>
<td>18.6</td>
<td>20.9</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td>( S_{m,VA} )</td>
<td>13.5</td>
<td>21.5</td>
<td>23.5</td>
<td>25.5</td>
<td>27.5</td>
<td>29.5</td>
<td></td>
</tr>
<tr>
<td>Phase A</td>
<td>5.1</td>
<td>9.6</td>
<td>13.1</td>
<td>12.5</td>
<td>7.0</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Phase B</td>
<td>2.2</td>
<td>3.2</td>
<td>3.0</td>
<td>2.7</td>
<td>1.9</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Phase C</td>
<td>5.2</td>
<td>7.5</td>
<td>5.7</td>
<td>6.5</td>
<td>3.8</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>( S_{m,VA} )</td>
<td>12.5</td>
<td>20.3</td>
<td>21.8</td>
<td>21.7</td>
<td>12.7</td>
<td>12.5</td>
<td></td>
</tr>
</tbody>
</table>
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-Vinacomín”

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 $K_{(u)}$ and $K_{p}$ exceed the normative values, and $\cos \varphi$ 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-Vinacomín."

### Acknowledgment

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### References


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