The optimization of the filter compensating devices parameters choice at the enterprises of agro-industrial complex

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Abstract: The optimization function of the filter compensating device has been determined, the purpose of which was the possibility of the harmonic distortion factor minimizing, the arguments of which are the power of individual filters. To analyze and compare the efficiency of the filter compensating device, quality indicators measurements of the electrical energy at an agricultural machine-building plant were made. Using the developed methodology for the filter-compensating devices optimal parameters calculating in the Mathcad software environment, the parameters selection and determination of two options of filter-compensating devices were made. According to the calculations, it was found that for the object under study, the most optimal, effective and economical device is a filter compensating one with a narrow-band filter tuned to the 5th harmonic and a wide-band filter of the 3rd order tuned to the 7th harmonic.

1. Introduction
The power supply per production unit of agro-industrial complex enterprises is constantly growing, approaching European standards. The modern technological process of agricultural enterprises often requires the use of powered converting equipment: rectifiers, inverters, thyristors, variable drives. This equipment has a non-linear voltage-current characteristic and is a source of current harmonics [1-3]. An increase in the share of this kind of load in the network leads to the electricity quality deterioration, which in turn affects not only the operation of individual enterprises and equipment, but also the power system as a whole [4-7].

Filter compensating devices (FCD) consist of capacitators, chokes and resistors, the connection of which allows you to obtain the frequency response of the network necessary to reduce harmonic distortion. In addition, due to the capacitive elements, connecting the FCD to the network contributes to the compensation of reactive power, which makes these devices highly commercial-effective. The research purpose is the calculating method development of the filter compensating devices optimal parameters in the Mathcad software environment and this method implementation on the example of an agricultural engineering enterprise.

2. Materials and methods
The filter-compensating devices connecting with the network in parallel affects the frequency response of the "network- FCD " circuit, which leads to a magnitude change of voltage harmonics at the common connection point of linear and non-linear loads. In this case, the frequency response of the specified circuit depends on the frequency response of the FCD, which is functionally dependent on its power \( Q \), quality factor \( d \) and tuning frequency \( s \). In this regard, one of the FCD selection stages is to find the function of the filter resistance on the relative frequency \( Z(k) \), the functional parameters of which are the filter power \( Q \), the quality factor \( d \) and the relative tuning frequency \( s \).

After resistances \( Z(k) \) functions determining for each of the filters, it is necessary to determine the function of the total resistance of the "network- FCD" circuit, it is found by the formula:
\[
Z(k, Q_1 \ldots Q_n) = \frac{1}{\sum_1^n \frac{Z_k}{Z}}
\]

(1)

where \(Z_k\), \(Z\) is resistance functions of the individual filters included in the FCD, Ohm; \(Z\) is network resistance function, Ohm.

According to [7], the network resistance at the fundamental harmonic can be calculated by the formula:

\[
Z_C = \frac{U_{nn}^2}{S_{kk}}
\]

(2)

where \(U_{nn}\) is nominal phase voltage of the network, V; \(S_{kk}\) is the short-circuit power at the connection point of the FCD, VA.

In this case, if there is no calculated complex value of the network resistance, then it is recommended to take the ratio of active resistance to inductive resistance as 9 to 1 [5].

The power selection of individual filters should be made from the condition of reducing the \(K_U\) values to the normalized values, while achieving the minimum possible \(K_U\) values is a priority task.

To be able to minimize the harmonic distortion factor in the Mathcad environment, it is necessary to set the \(K_U\) function, the arguments of which are the powers of individual filters:

\[
K_U(Q_1 \ldots Q_n) = \frac{100}{\sqrt{Z(2, Q_1 \ldots Q_n)I_2 + \cdots + Z(k, Q_1 \ldots Q_n)I_k}}
\]

(3)

Formula (3) includes summand of the form \(Z(k, Q_1 \ldots Q_n)\), which are the resistance of the "network-FCD" circuit at frequency \(k\), multiplied by the current of the \(k\)-th harmonic. This approach makes it possible to reduce the calculations inconvenience and to facilitate the calculation algorithm input in the Mathcad environment.

To minimize the function \(K_U(Q_1 \ldots Q_n)\), it is necessary to find its global extremum, characterized by the minimum function value for the admissible values of the arguments. The admissible values are set by some limitation, in this case, by the total power of the FCD individual links.

The final stage in the filter parameters selection is the calculation of the FCD each link individual elements: capacitance \(C\), inductance \(L\) and resistance \(R\).

To analyze and compare the FCD implementation effectiveness, the power quality indicators measurements were made at an agricultural machine-building plant. To carry out the calculation, the following data were obtained: single-line diagram of the enterprise; short-circuit power at the measuring point \(S_3 = 124\) MVA; power transformer type: TDNS-16000-35 / 6.3; \(U_k = 9.78\)%. During the enterprise analysis, it was revealed that the main source of harmonics current was the accelerating and balancing stand, designed for unwinding the machine shafts and their further balancing. Power units of the stand were two DC motors. At the same time, during the parts unwinding of the maximum dimensions and the operation of the balancing machine at rated power, failure of the switching power supplies and malfunctions in the operation of office equipment were observed, which is a characteristic sign of harmonic distortions in the network.

Measurements were carried out in the secondary circuits of devices in 6 kV switchgear with a Hioki PW3198 power quality analyzer using a 5A Hioki-9694 isolated current clamp. The measurements were carried out within an hour under various stand operating conditions. The measurement averaging interval was 1 s. Such a relatively short averaging time is necessary in order to achieve the required measurement accuracy and to carry out the analysis most objectively.

3. Results and discussion

To assess the need for compensation measures for reactive power, the values of the three-phase power consumed by the load and the power factor \(\cos(\varphi)\) averaged over the three phases were analyzed (Table 1).

The dynamics of the power consumed by the load shows that the load is of a changing nature, with periodic fluctuations reaching 2 MVA. According to table 1, the value of the total \(\cos(\varphi)\) varies in the range from 0.00 to 0.69, which is significantly lower than the normalized value.

The \(K_U\) coefficient reaches 13.17%, while an excess of 8% is observed during most of the measurement time, so we can talk about the discrepancy of this indicator with All-Union State Standard 32144-2013. Analysis of the partial coefficients \(K_{U(n)}\) values shows that most of the
coefficients reach values that they should not exceed within 100% of the time in accordance with All-Union State Standard 32144-2013.

**Table 1 - Power values and \( \cos (\phi) \) at the measuring point.**

| Power      | \( P \), kW | \( S \), kW | \( Q \), kW | \( \cos (\phi) \) | Standardized \( \cos (\phi) \) value |
|------------|--------------|--------------|--------------|----------------|-------------------------------------|
| Maximum value | 4 740.00     | 7 330.00     | 7 210.00     | 0.69            |                                      |
| Average value  | 2 396.02     | 6 558.20     | 5 964.06     | 0.36            | 0.93                                |
| Minimal value   | 0.00         | 40.00        | 40.00        | 0.00            |                                      |

To assess the current harmonics influence degree on the network and other consumers, graphs of the phase total coefficients of the harmonic voltage components were built (Figure 1).

![Figure 1 - Values of phase coefficients \( K_U \).](image)

To increase \( \cos (\phi) \) to normalized values, the required compensation power was calculated for each measurement interval, which reaches 5860 kVAr.

The choice of the input parameters of the FCD links, such as the tuning frequency \( s \) and the quality factor \( d \), should be based on the analysis of the load current frequency spectrum. The maximum values of the harmonic currents obtained during the measurements are shown in Figure 2.
Analyzing the frequency spectrum, it can be noted that the 5th and 11th harmonics are predominant, while the entire frequency spectrum is divided into pairs of harmonics with the numerical sequence $6n \pm 1$, in such cases the load is rectifier devices with a six-pulse converter circuit.

While choosing the number of FCD links, you need to focus on the value of the prevailing harmonics, as well as on the frequency distribution. In this case, the most appropriate are two options:

- application of a narrow-band filter tuned to the frequency of the 5th harmonic and the use of a wide-band filter tuned to the frequency of the 7th harmonic;
- the application of a narrow-band filter tuned to the 5th harmonic frequency and the use of a wide-band filter tuned to the 11th harmonic frequency.

Moreover, each of the options has its own pros and cons. On the one hand, taking into account the links tuned to the frequency of the 5th and 7th harmonics, the issue of resonance between the links at the frequencies of the prevailing harmonics is resolved, but at the same time, the power of the broadband filter may not be enough to suppress the 11th harmonic, i.e. to such filters have maximum efficiency at the tuning frequency. On the other hand, while filters application with a tuning frequency of the 5th and 11th harmonics, it is possible to effectively suppress the two most quantified harmonics, but resonances and voltage harmonics amplification at frequencies from the 5th to 11th harmonics are possible.

Considering two options for choosing the frequency of the FCD links tuning, we can say that in each case of various types filters applying the most effective option is the option with the links tuning to the 5th and 11th harmonics. With this choice of setting the following $K_U$ values were obtained as a calculations result: 2.38; 2.80; 2.37. This is due to the fact that in this case the 11th harmonic has a maximum value and when the filter is tuned to it, it is suppressed most effectively. When the links are tuned to the frequencies of the 5th and 7th harmonics, the calculated $K_U$ values are: 3.32; 2.89; 3.07.

However, not only the $K_U$ value is an indicator of the FCD application effectiveness. To comply with the norms, the partial coefficients $K_{U(n)}$ should also not exceed the values specified in All-Union State Standard 32144-2013. Analyzing the frequency characteristics, it can be noted that when the links are tuned to the 5th and 11th harmonics resonances arise between the tuning frequencies, this leads to an increase in voltage harmonics. This is also indicated by the calculated values of $K_{U(4)}$ and $K_{U(6)}$, these coefficients exceed the normalized values while links application at the 5th and 11th harmonics.
Comparing the solutions efficiency with different tuning frequencies, it can be argued that in this case, a more preferable solution is to use a filter with links tuned to the 5th and 7th harmonics.

The FCD application efficiency is also influenced by the type of used broadband links. Evaluating the each type of filter efficiency by the calculated $K_U$ values, we can say that the most effective is a filter with a narrow-band link and a third-order link tuned to the 5th and 7th harmonics, respectively. Figure 4 shows the surface plot for the $K_u(Q_1, Q_2)$ function using the above filter.

From the surface plot in Figure 3, it can be concluded that the filter efficiency is directly dependent on the filter power, and the more power, the higher the efficiency. This dependence shows that the FCD application is limited by the reactive power consumed by the load, and at its low values, such filters may be ineffective. In such cases, the only possible technical solution is the active harmonic filter application.

4. Conclusion

Using the developed methodology for the filter-compensating devices optimal parameters calculating in the Mathcad software environment two options of filter-compensating devices parameters were selected and determined.

According to the calculations, it was found that for the object under study the most optimal, effective and economical is a filter compensating device with a narrow-band filter tuned to the 5th harmonic and a wide-band filter of the 3rd order tuned to the 7th harmonic. This version of the filter-compensating device will have the lowest active losses, a high degree of harmonic voltage components reduction and does not lead to the resonance phenomena occurrence at the frequencies of the harmonic components.

References

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