Special aspects of application of filter-compensating devices in power supply systems with non-linear electrical receivers

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Abstract. This article presents special aspects of selection and application of filter-compensating devices (FCD), made on the basis of passive filters (PF), in power supply systems for various purposes with non-linear electrical receivers (ER). We show the features of various power supply systems with typical consumers of electrical energy. As an example, we consider power supply systems of 0.4 kV for detached houses and of 6-10 kV for industrial enterprises with high-power thyristor DC drives. We describe features of generating higher harmonics (HH) of current and voltage in the considered electrical networks, their harmonic composition and the main negative consequences. We consider main technical means of compensating HH of currents and voltages in power supply systems with nonlinear ER, and analysis of various PF types. The influence of frequency properties on HH compensation is presented as one of the main features of PF application in FCD. Special aspects of selection of PF specific types and its parameters are described on the basis of solving optimization problems. The main methods of FCD design optimization are considered. Based on FCD structure optimization, we proposed their most rational designs for various power supply systems, as well as the results of their application.

1. Introduction

In power supply systems of detached houses, the main consumers are low-power single-phase electrical receivers (ER), in which semiconductor elements with non-linear current-voltage characteristics are used, which generate higher harmonics (HH) into the network. In addition, all single-phase ER are connected to a three-phase four-wire network, which results in appearance of current and voltage asymmetries in power supply systems of detached houses. Modern industrial enterprises widely use powerful nonlinear consumers, which include power thyristor converters or controlled semiconductor rectifiers, for example, DC drives, made according to the TP-D system. The use of such a powerful power converter technology leads to generation of HH currents and voltages in supply high-voltage network of industrial enterprises.

A number of works describes the negative impact of HH currents and voltages, as well as asymmetric modes of operation on the elements of power supply systems of detached houses [1-4] and on high-voltage networks of industrial enterprises with powerful non-linear loads [5-8]. The main adverse effects of HH include: deterioration of quality indicators of electric energy; additional loss of active power in elements of power supply systems; reduced insulation service life; high probability of disrupting the normal operation of electrical equipment; impact on the operating modes of the entire system, as well as on consumers of electrical energy in particular.
2. The features of power supply systems

The main feature of power supply systems of detached houses is that the daily consumption of electricity is random in nature and depends on many factors: conditions of life, family labor regime, the degree of ER saturation. In addition, it depends on day of week and time of year. For private sector power supply systems, it is necessary to supply electricity to a significant amount of single-phase ERs dispersed over a large area. As a result, such networks are characterized by large extent and low load density. The main features of high-voltage networks of industrial enterprises include the presence of high-power semiconductor converters, made, for example, using 12-pulse rectifying circuits, as well as its intermittent operation mode.

The results of experimental studies, simulation and analytical calculations confirm that in high-voltage networks with powerful thyristor DC drives, the most pronounced are the canonical 11, 13, 23, 25, 35 and 37th harmonics of currents and voltages. The magnitude of non-canonical harmonics and interharmonics is well below the level of canonical harmonics, starting from the 11th. In networks of 6-10 kV with an isolated neutral, there are no physical prerequisites for generating the 3rd harmonic into the network due to the high requirements for phase symmetry. The low level of the 5th and 7th harmonics is provided by their compensation in valve windings of matching transformers. In low-voltage networks of 0.4 kV with a dead-earthed neutral, the 3rd and 5th HH of current and voltage are dominant, which are comparable to the magnitude of the main frequency.

The significant negative impact of HH caused by operation of high-power non-linear ER in high-voltage networks and single-phase ER in detached houses makes the task of compensating them particularly relevant.

3. FCD types

To compensate HH currents and voltages in power supply systems with nonlinear loads, various types of technical means can be used: passive filters (PF), active filters (AF), hybrid filters [9].

One of the most common, convenient and practically applicable technical means of compensating HH currents and voltages in power supply systems is PF, which, despite the appearance of active filters, remains in demand [10–13]. This is one of the most affordable, cheap and effective means of HH compensating and improving the electricity quality.

PFs have low cost, cost effectiveness, a fairly simple design, do not require regular maintenance, simultaneously perform the functions of HH attenuation and reactive power compensation, and have various configurations and implemented frequency characteristics. PFs are static devices, but they can be installed as part of an automated control system as separate stages tuned to the corresponding harmonics under dynamically changing load. At the same time, the efficiency of PF use will be significantly higher at approximately constant harmonic composition of currents and voltages, as well as at “hard” supply network structure. The disadvantage of PF usage is the possibility of resonance appearance in a parallel oscillating circuit formed by the filter, inductance and capacity of supply mains, at frequencies close to HH frequencies.

So, to compensate HH currents and voltages in power supply systems with non-linear consumers, it is advisable to use three-phase three-wire PF of various orders of magnitude, mainly with parallel connection, tuned to one or more HH frequencies. Also, application of PF harmonics is based on the analysis of technical and economic indicators of compensation efficiency of HH currents and voltages in industrial and private networks in the presence of non-linear consumers. The most common types of FS are: resonant (narrowband), second-order PF, third-order PF, C-type PF.

The main advantage of the resonant PF is efficiency of attenuation of harmonic components, frequency of which is close to the resonant frequency. However, its efficiency decreases with changing harmonic structure of currents and voltages or network parameters. Also there is a possibility of resonance occurrence in a parallel oscillatory circuit, formed by the filter and inductance of supply mains, at frequencies close to HH frequencies.

Second-order PFs are easy to use compared to first-order filters and have lower losses at fundamental frequency. Higher harmonics of current and voltage are reduced in a wider frequency
range. The disadvantages include high losses at fundamental harmonic frequency compared with that for a resonant filter.

Lower losses at fundamental frequency in a third-order filter as compared to that for a second-order filter ensure that HH current and voltage are reduced even in a wider frequency range, but they are rarely used in industry because of their high cost.

The C-type filter has the lowest power loss at the frequency of fundamental harmonics compared to that of all other filters and provides compensation of reactive power at fundamental harmonic frequency and HH attenuation. It has the following disadvantages: large scatter of capacitor nominals, high total capacity and high sensitivity to changes in fundamental frequency and deviations in elements parameters.

4. The influence of frequency properties on HH compensation
The network frequency response has a significant impact on transmission of HH currents and voltages from the source to the network. To establish the nature of HH generation in the network, a deep study of frequency characteristics of electrical networks on the basis of their complete equivalent circuits is required. The frequency characteristic of network significantly expands the concept of network operation at various composition and load variations on HH, warns of possible current and voltage resonances, and makes it possible to determine measures for HH compensating [14]. Therefore, one of the important criteria for choosing the types and parameters of PF is the influence of frequency characteristics of the “filter-external network” system. The installation of FCD in power supply systems causes a change in frequency properties of the system, and at the same time leads not only to more efficient compensation of certain harmonics, but also to an increase in non-canonical and inter-harmonics.

For specific nonlinear ER, resonant filters can be used to compensate the most pronounced canonical harmonics, for example, the 3, 5, 7, 11, and 13th harmonics. To compensate the harmonic components of higher-order currents, broadband filters are used. Broadband filters are tuned to higher order harmonics, for example, the 17th, 19th or 23rd harmonic components.

For example, the amplitude-frequency characteristic (AFC) of a high-voltage network of an ore mining industrial enterprise with a 12-pulse thyristor converter has poles at frequencies of 450, 900 and 1850 Hz (9, 18, 37 harmonics), caused by the reactive components of lines and transformers (Figure 1 a).
When installing resonant filters tuned to the 11th and 13th harmonics, together with broadband filters of the second order at frequencies of 550 and 650 Hz, the zeros of function appear, providing effective compensation of the corresponding harmonics, as well as complex attenuation of higher canonical harmonics takes place, starting with the 19th (Figure 1 b).

5. Conclusions

Thus, the choice of specific PF types to create the most optimal FCD structure requires solving a multicriteria optimization problem, which means choosing the best option at the same time according to many criteria. At the same time, solving optimization problems using classical objective functions and their minimization by 2-3 parameters may not give the best solution, appear to be too difficult to solve, do not cover all criteria and constraints, or may not have solutions at all. Therefore, nowadays the theory of fuzzy sets is widely used for solving problems of optimizing the modes of electric power systems [15, 16]. From a mathematical point of view, the solution of a multicriterial optimization problem allows one to choose the best option for the criteria of equal and various importance.

The existing methods for compensation of HH currents and voltages, selection of magnitude and location of FCD in power supply systems are based on minimizing active power losses and cost reduction [17, 18]. There are a number of drawbacks in the proposed solutions: the properties of frequency characteristics “filter - external network” are not taken into account, as well as power loss in FCD. In calculations, deterministic values of parameters of power supply systems and empirical formulas are used to take into account changes in the network resistance depending on the HH numbers. The use of methods based on fuzzy sets, allows one to make decisions by means of formalization of human ability to reason.

Based on optimization of the PF structure, the most rational FCD designs for various power supply systems are proposed, the results of which are presented in Table 1.
Table 1. Results of PF application in various power supply systems.

| Power supply system                      | Power supply system for detached houses                                                                 | Power supply system for ore mining industrial enterprise                                                                 |
|-----------------------------------------|-----------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Voltage class, kV                       | 0.4                                                                                                       | 6                                                                                                                        |
| Non-linear load                         | Gas discharge lamps; switching power supplies; frequency converters; uninterruptible power suppliers, etc. | Hoist units (HU) with electric drives, system-made thyristor converter - DC motor with outside excitation                 |
| The most pronounced canonical harmonics | 3, 5, 7th HH of currents and voltages                                                                    | 11, 13, 25, 25 and 37th HH of currents and voltages                                                                      |
| The harmonics being compensated         | 3, 5                                                                                                       | 11, 13, 23 and higher                                                                                                     |
| PF Types                                | Wideband PF of double tuning, tuned to compensation of the 3rd and the 5th harmonics; AF                  | Resonant PF, tuned to the 11th and 13th harmonics, and broadband filter of the second order, tuned to HH compensation starting from the 23rd |
| PF characteristics                      | \( L_{3PTL} = 10.3 \text{ mHn, } C_{3PTL} = 109.2 \mu \text{F} \)                                          | \( L_{11SHU} = 1.817 \text{ mHn, } L_{13SHU} = 1.672 \text{ mHn,} \) \( L_{11CHU} = 2.071 \text{ mHn, } L_{13CHU} = 1.905 \text{ mHn,} \) \( C_{11SHU} = 46.09 \mu \text{F, } C_{13SHU} = 35.87 \mu \text{F,} \) \( C_{11CHU} = 40.43 \mu \text{F, } C_{13CHU} = 31.47 \mu \text{F,} \) \( L_{23SHU} = 0.268 \mu \text{F, } C_{23SHU} = 71.43 \mu \text{F,} \) \( L_{23CHU} = 0.275 \text{ mHn, } C_{23CHU} = 69.71 \mu \text{F} \) |
| Places of installation                  | At three overhead lines supports, starting from the last one, every 100 meters of PTL 0.4 kV; at UTS tires | At a 6 kV switchgear on HV side of a matching transformer                                                                  |
| Reduced additional power loss,%         | 84                                                                                                         | More than 90                                                                                                             |

The use of the proposed PF structures allowed us to achieve the following results. The total harmonic components of current and voltage for the 0.4 kV PTL of power supply system for detached houses were \( K_I = 5.5 \% \), \( K_U = 2.2 \% \). As a result of compensation of the 3rd and 5th HH, additional losses of electricity in power supply system of detached houses decreased by 84\%, and amounted to \( \Delta W = 23 \text{ kW} \cdot \text{h} \) per day. The current in the neutral wire decreased to \( I_N = 0.8 \text{ A} \). The total harmonic components of current and voltage in high-voltage ore network decreased and amounted to: \( K_I = 3.72 \% \), \( K_U = 0.61 \% \) for high-voltage network of the skip hoist unit (SHU); \( K_I = 2.66 \% \), \( K_U = 1.2 \% \) for the cage HU (CHU) network. At the same time, when installing FCD, the additional total power losses caused by HH decreased by more than 90\% and amounted to \( \Delta P = 0.51 \text{ kW} \).

To increase the efficiency of PF using, as well as to eliminate the phenomenon of overcompensation of reactive power, we can propose installation of several PF levels tuned to the corresponding harmonics under dynamically varying loads. However, implementation of such a system requires additional research. In addition, the PF stage level control requires an additional automation system, which will increase the FCD cost.

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