E3S Web of Conferences **470**, 01023 (2023) https://doi.org/10.1051/e3sconf/202347001023
ESR-2023

Some factors constraining the development and implementation of power grid voltage harmonics of filter-compensating installations

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Abstract. The factors constraining the development and implementation of filter-compensating installations are considered. The data on the limit values of the parameters of the elements of resonant circuits and the degree of their influence on the quality factor are summarized. It is shown that the main criterion for the efficiency of filter-compensating installations is to ensure the resistance of a sequential resonant circuit significantly less than the impedance of the power grid.

1 Introduction

The development of the fundamentals of the filter compensating installations (FCI) design is an urgent task, which follows from the results of studying more than 50 publications [1-12] carried out over the past 15 years, mainly by the authors of three research teams in cities of Nizhny Novgorod, Krasnoyarsk and Irkutsk, as well as the new GOST (GOST - Russian National Standard) R 59032-2020 [13]. Attention should be paid to the fact that there are a number of factors that, to a certain extent, hinder the further development and implementation of higher harmonics of the power grid (PG). The various types of FCI described in publications, often also referred to as devices, usually consisting of several resonant circuits tuned to the initial odd harmonics, and a broadband filter connected in parallel to the power grid and a nonlinear load. The characteristic of the FCI and its functional capabilities are largely comprehensively determined by the values of the inductance of the coil (reactor) (L), the capacitance of the capacitor (C) and the additional resistor (R_{add}).

The use of combinations of very different values of the parameters of these elements in resonant circuits (RC) leads, respectively, to different characteristics of the FCI, many of which are often not given in publications. The initial data are often presented in such a combination and volume that it does not allow even specialists to analyze the technical characteristics of the FCI in detail on their own with subsequent systematization. This is to a certain extent due to the small amount of experimental confirmation of the results of computer modeling. The process of analyzing the FCI is also complicated by the fact that, unlike power transformers, generators, there is no list of parameters and regulatory requirements to them, which could form the basis for the development and quality control

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of FCI and, accordingly, contribute to their implementation. To understand the real situation in the design theory of the FCI, consider the ranges of variability of the values of the elements in the FCI – the inductance of the reactor (L), the capacitance of the capacitor (C), the resistance of the additional resistor (R_{add}) and the internal impedance of the power grid (PG) (Z_{PG}).

2 Information about the characteristics of FCI elements Inductance

The inductance of the RC coils in the considered works takes a value in a wide range from 0.235 mGh to several Gh. Because of this, the question arises as to how much such limits of its values are needed. To answer it, let's consider the dependence of the Q factor (Q) on the value of R_{add}, often used and connected in series with RC, which is determined by the characteristic resistance (ρ) calculated according to the formula:

$$\rho = L/C \qquad (1)$$

It follows from it that as the value of the inductance prevails over the capacitance of the capacitor, the value of ρ increases, and accordingly, the Q-factor Q of the resonant circuit, calculated according to the formula:

$$Q = \rho/R_{con} \qquad (2)$$

An excessively large Q-factor of the RC, as well as a small one, reduces the main characteristics of the FCI and therefore its value sometimes needs to be reduced to 30-40 [1, 2] by using an additional resistor R_{con}. A significant increase in the value of the inductance of the reactor over the capacity is accompanied by an increase in its resistance, which obviously does not allow obtaining a Q-factor value of more than 200-300.

The capacitor. The value of the capacitor capacitance in the analyzed publications ranges from 0.342 μF to 3875 μF. From this it can be seen that the multiplicity of changes in the capacitance of the capacitor reaches 10000. This variability affects the spread of the values of ρ and Q and raises great doubts about its necessity.

Additional resistor. It is used in a number of FCI models, as already mentioned above, to reduce the quality factor to the required level. The publications cite a variety of values of the resistance of the additional resistor (R_{add}) and without an appropriate explanation. In some works, it is chosen excessively large and equal to 14-37 ohms [1], in the second – equal to 1.0-5.4 Om [10, 14], in the third – insignificant, at the level of 0.1 -0.2 Om [4, 9]. It is unclear from the publications whether these are really tuning resistors or in this way the authors indicate the resistance of the reactors. There are also many models of FCI in which R_{add} is not given at all against the background of the lack of information about the resistance of the reactor. In this case, R_{con}, when resonance occurs in the RC, will be equal to the resistance of the inductor r_L.

Most of the FCI are the result of numerical modeling, that is, they are proposed without experimental approbation. Probably for this reason, the R_{add} varies within very large limits (from 0.01 to 37 Om). Additional calculations show that it is very overestimated in [1], obviously with the aim of lowering the Q-factor of the RC on all suppressed harmonics to 41. The addition of these resistors to the RC circuit leads to a significant decrease in their selectivity.

The Q-factor of the resonant circuit. Selecting specific values of L, C and $R_{con} = (r_L + R_{add})$ determines the Q-factor value in aggregate. Due to the large range of variability of these parameters, the calculated Q-factor value according to our data also varies within very large limits, which is clearly shown in Table 1.

Table 1. Calculated values of the characteristic resistance and Q-factor for different models of FCI.

No.	The type of FCI and the values of resonant frequencies	ρ, Om	Q at r_L=0,20 Om	Source of literature
1	Three single-link filters connected in parallel F1=242 Hz; F2=246 Hz; F3=964 Hz	0,21 0,38 0,41	1,1 1.9 2,1	Dovgun V.P., Boyarskaya N.P., Novikov V.V.PE. 2011. No. 9-10. pp. 31-39
2	Three single-link filters connected in parallel F1=242 Hz; F2=346 Hz; F3=964 Hz	1,3 6,3 1,7	7,0 31 8,0	Valeev I.M., Alzakkar A.M.-N. Bulletin of the KSEU, 2020, No. 1(45), pp. 24-39.
3	F =248 Hz	31 122 (Rmin 3,4 Ом)	6,0 33	Kuleshova G.S. Abstract, M., MEI, 2023, 20 p.
4	Single-link filter F=250 Hz	19	95	The website of JSC "Idis Group"
5	Two single-link filters F1=142 Hz; F2=142 Hz; F3=240 Hz	101 152 83	505 760 415	German L.A., Serebryakov A.S., Maksimova A.A. Newspaper VNIJT, 2016, Vol. 75, apostille 1, pp. 26-34.

Note. When calculating Q, the minimum value of the reactor r_L was assumed to be 0.2 Om.

This indicator, which integrally characterizes each FCI model, is practically not given in publications. Its calculation shows that it can differ 3-5 times even within the RC of each publication, while the difference between the data of different authors can be 100-1000 times. This situation should affect the effectiveness of harmonic suppression for each circuit. It is proposed to carry out an objective assessment of the FCI primarily by the coefficient of efficiency of suppression of higher harmonics (K_{eff}) [15] according to the following formula:

$$K_{eff} = K_{u\ base} / K_{u\ FCI}, \qquad (3)$$

where $K_{u\ base}$ – the coefficient of nonlinear distortion without FCI, $K_{u\ FCI}$ – the same coefficient, but with the use of FCI.

FCI should be perceived as an electrical design that is not inferior in importance, for example, to transformers and generators. Therefore, it was necessary to develop and propose such indicators that could reliably and promptly characterize the FCI. Based on the analysis of one of the early models of FCI, it is shown how many indicators are missing in [1, 4, 6] and other works. A detailed analysis of the characteristics of the FCI allowed us to conclude that the model presented without testing was not suitable for use in PG. For an operational and express assessment of the suitability of the FCI, the inequality is proposed [15]:

$$Z_{PG} >> R_{con} << Z_{load} \qquad (4)$$

where Z_{load} is the impedance of the total load at the point of its connection.

According to (4), the active resistance of each RC should be significantly less than the impedance of the PG and the resistance of the nonlinear load. If even one condition $Z_{PG} >> R_{con}$ is met, the FCI will not only lower the higher harmonics (HH) of the PG voltage, but also the HH currents of the nonlinear load, since in this case they will also be shunted by the circuit. The second condition is $R_{con} << Z_{load}$ when performing the first one will always be performed, because according to the calculations of Z_{load} , depending on the voltage class, PG has values ranging from 1 to 100 Om. At the same time, the main condition is difficult to fulfill, since the absolute value of the impedance of the PG according to different sources is commensurate with r_L (from 0.1 Om [4] to 1 Om [16). The satisfactory efficiency of the FCI will have, starting from r_L less than 2 Z_{PG}. To effectively suppress harmonics, it is necessary that the resistance r_L be an order of magnitude less than Z_{PG}.

The reactive power of RC capacitors additionally contributes to a certain extent to a positive phase shift of the inductive component of the current in the PG, and, accordingly, to an increase in the power factor of the PG. Thus, only the FCI satisfying the conditions of inequality (4) will weaken the HH voltage of the PG, the currents of the nonlinear load.

In [15], based on the study of a large number of publications, an approximate list of indicators intended for the formation of technical characteristics of the FCI is proposed. When managing the values of these indicators, the analysis of the model under consideration will be significantly facilitated and accelerated.

There is practically little work in the development methodological and methodological issues, which accordingly affects, as in other areas, the pace of research, the reliability of the results obtained and their implementation. We need a common terminology, regardless of the scope of its application, to avoid discrepancies. For example, in power engineering, when describing the resonant circuits of FCI links, the term "reactor" is mainly used, which is not accepted in radiophysics. The peculiarity of reactors in the power industry is the absence of transformer iron in them, while in inductors used in FCI, transformer iron is usually used as a core. The latter devices are usually referred to as throttles in all areas of their application.

There are isolated cases when a similar term is used in the description of FCI. According to its definition and purpose, this term is essentially also of little use for naming the RC inductor. Temporarily, it is possible to limit the use of the term "reactor", since no proper replacement has been proposed yet. The problem also lies in the fact that the websites of manufacturers do not provide the values of the active resistance of throttles and reactors, since according to their information this parameter is not included in regulatory documents.

In addition, two terms such as devices and installations are used as synonyms for filter-compensating products. It is advisable to use them in conjunction with the nominal value of the operating voltage class, as well as the weight, dimensions and price of the FCI. In general, when suppressing a number of harmonics in three-phase networks, this is an entire installation, which prompted the use of this term in the work. Occasionally, it is also used in individual works on FCI.

So far, such important technical characteristics of the FCI as the harmonic suppression efficiency coefficient of the FCI, the normative power loss as a percentage, the permissible coefficient of nonlinear distortion of the mains voltage and some others have not been considered collectively.

The magnitude of the RC frequency detuning is one of the important characteristics of the FCI, since it largely determines the effectiveness of the suppression of HH. In many, especially early, works, there is no information about the presence of a frequency disorder of RC. An explanation of the need for its application can rarely be found in publications. In a number of papers, the authors write that the frequency of the contours is tuned exactly to the frequency of the harmonic. Meanwhile, an additional calculation of the resonant frequencies of the RC shows (Table. 1) that they are actually in these works less than the frequencies of harmonics.

Frequency detuning, according to many works, is provided for correcting for aging, primarily of capacitors [7, 13, 14]. In individual works, empirical limits of the deviation of the frequency of the FCI by 3-10% from the suppressed harmonic are proposed, but without substantiating the need for this technique and specifying its values [9, 13, 16, 17]. If we are guided by the permissible limit of capacitor aging, in accordance with the known GOST (-3%), then the detuning value should not exceed 1.5%, and this is essentially commensurate with the accuracy of the frequency tuning of the RC itself. Frequency detuning, in fact, should be provided from the condition of preventing the occurrence of a resonance of currents in the ES, and, accordingly, increasing the voltage level of individual voltage harmonics and determined by the value of the Q-factor provided by the RC. As for the instability of the PG frequency itself, it can be neglected, since it does not exceed 0.1% [18].

It follows from the above that for the design of the FCI, it is necessary to develop a method for complex determination of the detuning value, taking into account the Q-factor of the resonant links circuit, the speed and acceptable limits of aging of the circuit elements and the necessary level of suppression of higher harmonics.

As for the unified form of representation of the amplitude-frequency characteristics (frequency response) of the FCI, it is also absent – it is given relative to the impedance, conductivity or current without taking into account the specific value of the impedance of the PG. For this reason, they are not informative enough in the presented form and are not suitable for assessing the filtering ability of the FCI. The nature of harmonic suppression will be more clearly visible if the amplitude-frequency response of the FCI leads by voltage and directly taking into account the initial impedance of each PG, which is practically not yet implemented. Another, more visual characteristic of the FCI, for express evaluation, can be the proposed suppression coefficient of higher harmonics [15].

3 Conclusion

To ensure filtering of higher harmonics of industrial frequency filter compensating installations, it is necessary that the impedance of the resonant circuits be significantly less than the input impedance of the electrical network. The quality of operation of filter compensating installations should be assessed by the value of the suppression coefficient of higher harmonics.

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