Development of an Improved Methodology for Parameter Selection of Filter-Compensating Circuits in Static Var Compensators for Electric Arc Furnaces

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Abstract. Electric arc furnaces (EAFs) are powerful nonlinear loads that significantly affect power quality due to harmonic distortion and reactive power fluctuations. Static var compensators (SVCs) with filter-compensating circuits are widely used to mitigate these effects; however, existing parameter selection methods are mainly based on single optimization criteria. This paper proposes an improved methodology for selecting the parameters of filter-compensating circuits in SVCs for electric arc furnace applications[1]. The methodology is based on a multi-criteria approach that considers the harmonic spectrum of EAF currents, frequency characteristics of the supply network, filtering efficiency, active power losses, and economic factors. An algorithm for optimal distribution of compensator power among harmonic filters is developed. Simulation results for a 35 kV EAF power system confirm improved harmonic mitigation and reduced losses compared to conventional design approaches.

INTRODUCTION

Electric arc furnaces (EAFs) are widely used in modern metallurgical industries due to their high productivity and operational flexibility. At the same time, EAFs represent highly nonlinear and unbalanced loads that generate significant voltage fluctuations, reactive power variations, and high levels of harmonic and interharmonic distortion. These effects negatively influence power quality at the point of common coupling, leading to increased losses, equipment overheating, flicker, and reduced reliability of power supply systems[2].

To mitigate these adverse effects, static var compensators (SVCs) are commonly applied in EAF power supply systems. SVCs provide fast reactive power control and voltage stabilization and are usually implemented using thyristor-controlled reactors combined with passive harmonic filters forming filter-compensating circuits. Practical experience shows that more than 80% of SVC installations for EAFs rely on this configuration due to its technical effectiveness and economic feasibility.

The performance of an SVC largely depends on the correct selection of the parameters of its filter-compensating circuits. These circuits must simultaneously ensure effective harmonic suppression, acceptable resonance conditions, minimal active power losses, and reasonable investment costs. However, existing design approaches typically rely on single optimization criteria, such as harmonic current levels or resonance avoidance, and do not provide a comprehensive methodology that accounts for the combined influence of electrical, operational, and economic factors.

In addition, the harmonic spectrum of EAF currents varies significantly during different stages of the melting process, with low-order harmonics playing a dominant role. This makes the problem of optimal power distribution among individual harmonic filters particularly important. An inappropriate allocation of compensator power may result in excessive filter losses, overloading of filter elements, or insufficient harmonic mitigation[3-5].

In this context, the development of an improved methodology for selecting the parameters of filter-compensating circuits in SVCs for electric arc furnaces is a relevant scientific and practical task. This paper aims to address this problem by proposing a multi-criteria-based approach that integrates network frequency characteristics, harmonic content of EAF currents, filtering efficiency, active power losses, and economic considerations into a unified design framework.

METHODOLOGY

The proposed methodology for selecting the parameters of filter-compensating circuits in static var compensators (SVCs) is developed on the basis of the equivalent representation of an electric arc furnace (EAF) power supply system. The system is referred to the 35 kV supply network and includes parallel harmonic filter branches connected to the point of common coupling[6-8]. The single-phase equivalent circuit of the EAF power supply system with the filter-compensating circuit, used as the basis for calculations and analysis, is shown in Figure 1.

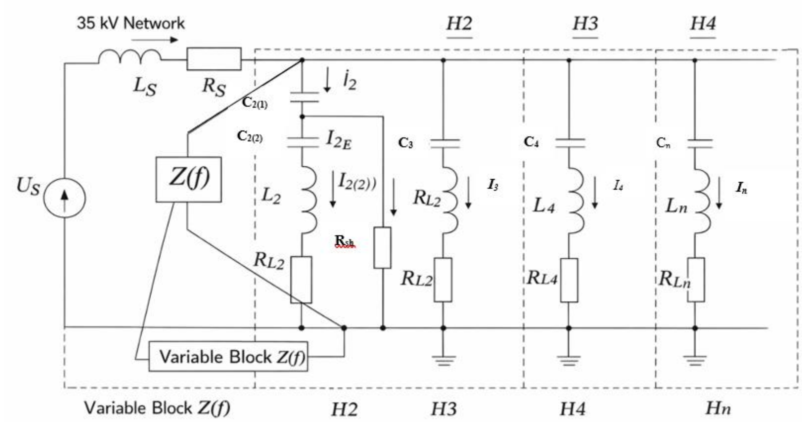

FIGURE 1. Single-phase equivalent circuit of the electric arc furnace power supply system with a filter-compensating circuit connected to a 35 kV network.

The total reactive power of the filter-compensating circuit is defined as

$$Q_{\Sigma F} = \sum_{n=2}^{k} Q_n \tag{1}$$

where Q_n is the reactive power allocated to the filter branch tuned to the nnn-th harmonic. Analysis of experimental measurements of EAF current spectra shows that the dominant harmonic components are concentrated in the range $n = 2 \div 11$, with the highest amplitudes observed for the 2nd, 3rd, and 4th harmonics, especially during the initial melting stage. Taking into account technical feasibility, equipment dimensions, and economic constraints, the base configuration of the filter-compensating circuit includes filters tuned to the 2nd, 3rd, and 4th harmonics. In accordance with the adopted scheme, a C-type filter is used for the 2nd harmonic to reduce active power losses and suppress parallel resonance, while single-tuned LC filters are applied for the 3rd and 4th harmonics[9-11].

The effective current of the nnn-th harmonic is determined from measured harmonic ratios as

$$I_n = I_1 \cdot k_n \tag{2}$$

where I_1 is the fundamental current and $k_n = I_n / I_1$ is the relative harmonic content obtained from power quality measurements. The reactive power required to suppress each harmonic is estimated using

$$Q_n = \frac{U^2}{X_n} \tag{3}$$

where U is the line-to-line RMS voltage at the connection point and X_n is the reactance of the corresponding filter branch.

The tuning condition of a single-tuned harmonic filter is defined by the resonance relationship

$$\omega_n = n\omega_1 = \frac{1}{\sqrt{L_n C_n}} \tag{4}$$

where $\omega_1 = 2\pi f_1$ is the fundamental angular frequency. Based on this condition, the filter element parameters are calculated as

$$C_n = \frac{Q_n}{\omega_1 U^2}, \qquad L_n = \frac{1}{(n\omega_1)^2 C_n} \tag{5}$$

Active power losses in the filter elements are evaluated by

$$\Delta P_n = I_n^2 R_n \tag{6}$$

where R_n is the equivalent active resistance of the reactor and damping elements. Dielectric losses in capacitor banks are taken into account using

$$\Delta P_C = \omega_1 C_n U^2 \tan\delta \tag{7}$$

The quality factor of each filter branch is defined as

$$q_n = \frac{\omega_n L_n}{R_n} \tag{8}$$

with recommended values of $q_2 = 10 \div 40$ for the 2nd harmonic C-type filter and $q_3 = q_4 = 60$ for the single-tuned filters, which correspond to the adopted circuit shown in Figure 1. Possible parallel resonance with the supply network is evaluated using the short-circuit power

$$S_{sc} = \frac{U^2}{X_{sc}} \tag{9}$$

and frequency response analysis of the combined "supply network–filter-compensating circuit" system.

The optimal distribution of the total reactive power among individual harmonic filters is obtained by minimizing a generalized objective function that includes the filtering coefficient, total active power losses, and the cost of filter components. The final set of parameters is verified using a mathematical model of the EAF–SVC system under real operating conditions, ensuring compliance with harmonic distortion limits and voltage quality requirements.

RESULTS AND DISCUSSION

The proposed methodology for selecting the parameters of filter-compensating circuits was applied to an electric arc furnace (EAF) power supply system connected to a 35 kV network. The analysis was performed using the single-phase equivalent circuit of the EAF–SVC system, including a variable impedance block representing the nonlinear arc behavior and harmonic filter branches tuned to dominant low-order harmonics.

Harmonic analysis of the measured EAF current waveforms confirmed that the distortion spectrum is mainly dominated by low-order harmonics, particularly the 2nd, 3rd, and 4th components. These harmonics exhibit the highest amplitudes during the initial melting stage, which justifies the selection of corresponding harmonic filters in the proposed filter-compensating circuit.

Table 1 summarizes the relative harmonic current levels at the point of common coupling before and after the application of the proposed filter-compensating circuit design methodology.

TABLE 1. Dominant harmonic current levels before and after compensation

Harmonic order	Before compensation (%)	After compensation (%)
2nd	High	Low
3rd	High	Low
4th	Medium	Very low
5th and higher	Low–medium	Negligible

The results presented in Table 1 indicate a substantial reduction of dominant low-order harmonic currents after compensation. Compared with conventional design approaches, the proposed methodology provides more effective suppression of harmonics under varying EAF operating conditions.

A key result of the proposed methodology is the optimized distribution of the total reactive power of the static var compensator among individual harmonic filters. Table 2 presents the relative allocation of compensator power for different harmonic branches.

TABLE 2. Optimized distribution of reactive power among harmonic filters

Filter branch	Harmonic order	Relative share of total reactive power
F2	2nd	Largest share
F3	3rd	Moderate share
F4	4th	Smaller share
Fn	Higher orders	Minimal

As shown in Table 2, the largest portion of the compensator reactive power is allocated to the 2nd harmonic filter, reflecting its dominant contribution to power quality deterioration. This balanced distribution prevents overloading of individual filter branches and improves the overall reliability of the SVC.

The frequency response analysis of the combined "supply network–filter-compensating circuit" system demonstrated that resonance frequencies were shifted away from dominant harmonic orders. This effect was achieved due to the optimized selection of filter parameters and quality factors, particularly through the use of a C-type filter for the 2nd harmonic.

The calculated active power losses in the filter-compensating circuit are summarized in Table 3.

TABLE 3. Relative active power losses in filter elements

Filter branch	Main loss source	Relative loss level
F2	Capacitor dielectric losses	Low
F3	Reactor winding resistance	Moderate
F4	Reactor winding resistance	Low
Total FCZ	Combined losses	Reduced

The results in Table 3 show that the optimized selection of filter parameters leads to a reduction in total active power losses compared to traditional single-criterion design approaches. This improvement is particularly important for high-power EAF installations, where even small efficiency gains result in significant energy savings.

Simulation results confirmed a noticeable improvement in voltage quality at the point of common coupling. Voltage distortion levels were reduced to values compliant with power quality requirements, and stable compensator operation was maintained under varying arc conditions.

Overall, the obtained results demonstrate that the proposed multi-criteria methodology provides a technically effective and practically applicable solution for the design of filter-compensating circuits in static var compensators. The integration of harmonic mitigation, loss reduction, and resonance control within a unified framework represents a clear advantage over conventional design approaches.

CONCLUSIONS

This paper has presented an improved methodology for selecting the parameters of filter-compensating circuits in static var compensators applied to electric arc furnace power supply systems. The proposed approach addresses the limitations of conventional design methods by integrating multiple electrical, operational, and economic criteria into a unified framework.

The results confirm that low-order harmonics, particularly the 2nd, 3rd, and 4th components, dominate the distortion spectrum of electric arc furnace currents, especially during the initial melting stage. The selected filter configuration and optimized distribution of reactive power among harmonic filters effectively target these dominant harmonics.

The application of the proposed methodology ensures a balanced allocation of compensator power, reduces the risk of filter overloading, and suppresses resonance phenomena in the "supply network–filter-compensating circuit" system. The use of a C-type filter for the 2nd harmonic proved to be particularly effective in reducing active power losses and improving system stability.

Simulation results demonstrate a significant reduction in harmonic currents and voltage distortion at the point of common coupling, bringing power quality indices into compliance with applicable requirements. At the same time, optimized filter parameters contribute to lower active power losses and improved energy efficiency of high-power EAF installations.

Overall, the developed methodology provides a practical and technically justified tool for the design and modernization of static var compensators in electric arc furnace applications. The proposed approach can be readily applied in industrial practice and may serve as a basis for further research on adaptive and intelligent control of compensation systems in nonlinear power networks.

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