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EFFECT OF HIGH-CURRENT CIRCUIT SYMMETRIZATION ON ELECTROTHERMAL CONDITIONS IN A SIX-ELECTRODE SUBMERGED ARC FURNACE

WPŁYW SYMETRYZACJI TORU WIELKOPRĄDOWEGO NA WARUNKI ELEKTROTERMICZNE PIECA REZYSTANCYJNO-ŁUKOWEGO SZEŚCIOELEKTRODOWEGO

***Summary**: This study evaluates the effect of the planned symmetrization of the high-current circuit of a six-electrode submerged arc furnace on the electrothermal conditions of ferrosilicon smelting. The analysis was based on one week of operating data from one side of the six-electrode furnace, subjected to statistical processing, and on a physical similarity analysis referenced to a model furnace. It was shown that the existing power supply system is characterized by significant phase impedance asymmetry, which necessitates higher loading of the central electrodes in order to maintain proper thermal conditions in the reaction zones. It was also found that the measurements of secondary electrode currents are affected by a systematic error, and that the actual furnace operating state corresponds to a configuration consistent with the results of the physical similarity analysis. The obtained results indicate that simplified symmetrization of the high-current circuit, carried out without changing the transformers or the connection system, does not guarantee an improvement in the technical and economic performance indicators of the process. In the case investigated, the asymmetry of the power supply system performs a compensatory function and may contribute to maintaining more favorable process conditions than a formally symmetrical but structurally constrained system.*

***Keywords**: submerged arc furnace, ferrosilicon, high-current circuit, impedance asymmetry, furnace transformer, physical similarity, thermal conditions of reaction zones*

Streszczenie: W pracy oceniono wpływ planowanej symetryzacji toru wielkoprądowego sześcioelektrodowego pieca rezystancyjno-łukowego na warunki elektrotermiczne wytopu żelazokrzemu. Analizę oparto na tygodniowych danych eksploatacyjnych jednej strony pieca sześcioelektrodowego, poddanych obróbce statystycznej, oraz na analizie podobieństwa fizycznego odniesionej do pieca wzorcowego. Wykazano, że istniejący układ zasilania cechuje się istotną asymetrią impedancji fazowych, która wymusza większe obciążenie elektrod środkowych w celu utrzymania właściwych warunków cieplnych w strefach reakcyjnych. Stwierdzono również, że pomiary wtórnych prądów elektrod są obarczone systematycznym błędem, a rzeczywisty stan pracy pieca odpowiada konfiguracji zgodnej z wynikami analizy podobieństwa fizycznego. Uzyskane wyniki wskazują, że uproszczona symetryzacja toru wielkoprądowego, realizowana bez zmiany transformatorów i układu połączeń, nie gwarantuje poprawy wskaźników techniczno-ekonomicznych procesu. W badanym przypadku asymetria układu zasilania pełni funkcję kompensacyjną i może sprzyjać utrzymaniu korzystniejszych warunków procesu niż układ formalnie symetryczny, lecz ograniczony konstrukcyjnie.

Słowa kluczowe: piec rezystancyjno-łukowy, żelazokrzem, tor wielkoprądowy, asymetria impedancji, transformator piecowy, podobieństwo fizyczne, warunki temperaturowe stref reakcyjnych

Introduction

Contemporary ferroalloy metallurgy operates under increasing pressure to reduce process energy intensity, improve cost efficiency, and mitigate environmental impacts. For this reason, the modernization of electrothermal equipment cannot be assessed solely in terms of increased production capacity, but should also be evaluated with regard to energy efficiency, productivity, and the overall competitiveness of the enterprise. The literature emphasizes that sustainable modernization of the energy and industrial sectors requires knowledge transfer, the implementation of innovation, and systematic improvement of technical infrastructure, while solutions aimed at improving energy efficiency may simultaneously generate economic, environmental, and social benefits [1, 2]. Considerable importance is also attached to the digitalization of industrial processes in accordance with the Industry 4.0 concept, which may contribute to improved energy and material efficiency and support more rational process management [3].

In this context, the selection of furnace configuration becomes a matter of particular importance with respect to the technological requirements of the process [4–8]. In the case of highly energy-intensive alloys, such as FeSiAl, the ability to achieve a high concentration of energy within the furnace bath working space and a favorable distribution of heat among the reaction zones is of fundamental significance [9,10]. Industrial FeSiAl smelting campaigns carried out at Re Alloys indicate that a six-electrode furnace equipped with two 7.75 MVA transformers ensures an optimal distribution of power within the furnace and promotes intensive energy input into the bath and reaction zones [9,10]. This implies that, in furnaces of this type, constructional and electrical issues must be considered jointly with the requirements of the metallurgical process, particularly when highly energy-intensive operations are involved [4, 9–11].

The smelting of ferrosilicon containing at least 75 wt.% Si (FeSi75) in submerged arc furnaces belongs precisely to this category of processes, in which the electrical parameters of the power supply system and the thermal-technological parameters of the furnace remain closely coupled [4, 12–18]. This interdependence is particularly evident in six-electrode furnaces supplied by 2 × 7.75 MVA transformers, where the geometrical configuration of the high-current circuit, the routing of the conductors, and the electrode arrangement directly affect current distribution, electrode positioning in the furnace, and, consequently, the temperature field distribution within the reaction zones [13, 19–24]. In practice, this means that strictly electrical criteria, such as impedance symmetry or uniform phase loading, cannot be analyzed independently of process technology [4, 19, 20, 25–29]. In electrothermal ferrosilicon smelting, the thermal conditions prevailing in the reaction zones remain the primary criterion for selecting operating parameters, since it is within these zones that the principal physicochemical processes responsible for process efficiency and production stability take place.

The main objective of this paper is to provide a scientific interpretation of the arguments concerning the influence of high-current circuit symmetrization on furnace operating conditions and, subsequently, to assess whether simplified symmetrization of the system in a 2 × 7.75 MVA furnace can realistically improve the course of the ferrosilicon smelting process.

Characteristics of the power supply system and the asymmetry problem

The subject of the analysis is a six-electrode submerged arc furnace intended for the production of high-silicon ferrosilicon alloys (FeSi75). The power supply system is based on two furnace transformers, each rated at 7.75 MVA. On the secondary side, a star configuration is applied (Fig. 1), while current is delivered to the electrodes through an extensive high-current circuit composed of water-cooled tubular conductors.

The high-current circuit itself constitutes a three-dimensional system in which the lengths of the conducting sections, their routing, conductor transposition, and mutual magnetic interactions determine the resistive and reactive parameters of each phase [13, 21–24, 30–32]. The furnace under consideration is currently operated with electrodes of 900 mm in diameter. A schematic diagram of the furnace and electrode arrangement is shown in Fig. 2.

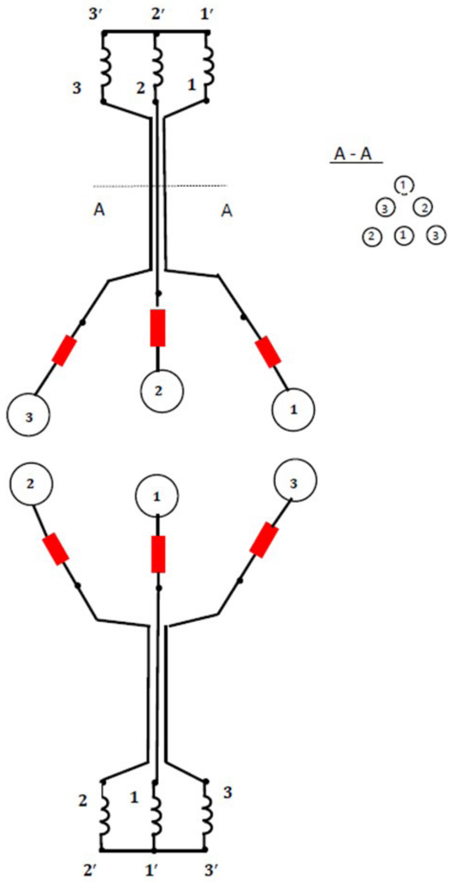

Fig. 1. Configuration of the high-current circuit of the six-electrode SAF [own work]

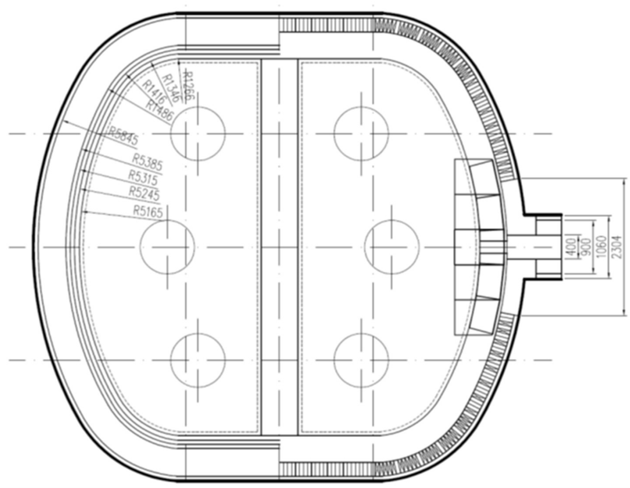

Fig. 2. Six-electrode SAF layout [own work]

Ferrosilicon smelting in a submerged arc furnace is highly sensitive to the local power distribution, because the process takes place in a heterogeneous medium comprising solid materials, a liquid phase, and reaction gases [4, 12, 14, 15, 33]. Unlike simple heating systems, the relationship between the current magnitude and the resulting thermal effect is indirect and depends both on the distribution of the electric field and on the changing physicochemical properties of the burden [4, 20, 23, 24,

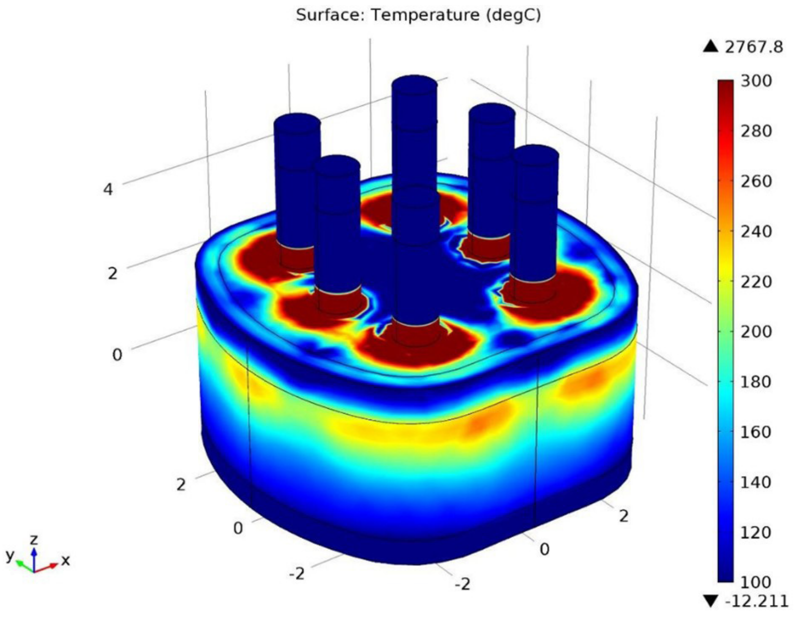

Fig. 3. Temperature field on the external surface of six-electrode SAF shell [31]

33]. Consequently, the thermal effect is not a simple function of the rms current value, but rather the result of the interaction of a number of phenomena occurring within the reaction zone.

An increase in electrode current loading leads to an increase in the power dissipated in its vicinity; however, the manner in which this energy is utilized depends on the local properties of the burden materials, in particular the carbonaceous reductants [4, 34–39]. From a technological standpoint, therefore, not only the amount of energy supplied to the system is important, but also the depth of its penetration into the burden and its ability to ensure conditions favorable for the effective reduction of silica.

In a six-electrode furnace, the electrodes do not operate as independent systems because their thermal and electrical fields partially overlap, as shown in Fig. 3.

Consequently, under certain conditions, the non-uniform loading of one of the electrodes may perform a compensatory function with respect to the thermal asymmetry of the entire system. If the central phase is characterized by more favorable current-flow conditions, its higher load may contribute to stabilization of the overall temperature distribution in the furnace [20–24, 40–42].

The significance of this mechanism becomes particularly evident when two different evaluation criteria are compared: the electrical criterion and the technological criterion. From the standpoint of the metallurgical process, the primary requirement is to ensure appropriate thermal conditions in all reaction zones, even if this is achieved at the expense of maintaining a certain degree of load asymmetry. Accordingly, a mode of operation should also be regarded as technologically unfavorable if – despite appearing correct from the standpoint of the electrical system – it does not provide the process intensity required. Such a condition may lead to reduced productivity, lower silicon recovery, and increased specific energy consumption. For this reason, optimization of the power supply system should be subordinated primarily to the thermal requirements of the process rather than exclusively to criteria of electrical symmetry.

One of the most important practical limitations of the furnace under investigation is its low control flexibility, which results from the characteristics of the 7.75 MVA transformers. The parameters of the six-electrode furnace transformer are presented in Table 1.

In an ideal system, the operator or the automatic control system should have access to a sufficiently dense range of voltage levels to enable precise adjustment of current and power to the current burden condition, electrode immersion depth, and instantaneous thermal conditions. In the furnace under consideration, the available control range is less favorable, and

Table 1. Furnace transformer parameters [own work]

Tap no.	Power (kVA)	Primary current (A)	Primary voltage (V)	Secondary current (A)	Secondary voltage (V)
1	7750	722,0	6200	29600	151,2
2	6970	646,0	6200	29600	136,0
3	6330	590,0	6200	29600	123,5
4	5790	539,0	6200	29600	113,0
5	5330	497,0	6200	29600	104,2
6	4970	462,5	6200	29600	97,0

the steps between the tap positions in use – particularly 136 V and 151.2 V – are sufficiently large that selecting a compromise operating point for all electrodes becomes difficult. This seemingly technical feature is of fundamental importance for the evaluation of symmetrization. If, after modernization, all phases were to operate under identical parameters, the limited number of tap positions would effectively force the furnace to choose between two imperfect operating states. Either all electrodes would operate at the lower voltage, which would improve the transformer safety margin but reduce the achievable power and potentially deteriorate the technological conditions, or all electrodes would operate at the higher voltage, which would increase process intensity but at the same time increase the overload of the entire system.

Materials and methodology

The analysis was based on measurement data collected from the Aveva Historian and InnADA.EE systems for one side of the six-electrode furnace during the one-week period. The data were originally recorded at 1 s intervals and were subsequently processed by down-sampling them to a 180 s interval and filling missing values with average values from short furnace downtime periods. On this basis, statistical characteristics were developed for electrode current loads, transformer primary currents, phase impedances and resistances, as well as active power, reactive power, power factor, and furnace electrical efficiency. In this case, the use of statistical analysis served a dual purpose: first, it made it possible to determine the actual operating state of the furnace during the analyzed period, and second, it enabled the identification of discontinuities and inconsistencies in the measurement data [43, 44].

The first important finding was the observation that the average current of the central electrode on one side was 31.712 kA, whereas the average currents of the side electrodes were 28.239 kA and 28.333 kA, respectively. Under these conditions, the furnace achieved an average active power of 5.883 MW and an average power factor of 0.7559, which corresponded approximately to the maximum apparent power of the 7.75 MVA transformer. This result already suggested that the furnace was being operated close to the limits of the power supply equipment, and that the higher loading of the central electrode was not incidental but rather constituted a normal element of the operating practice. This operating approach may be linked to the observed improvement in technical and economic performance indicators during the period in which greater attention began to be paid to the influence of power supply asymmetry on electrode positioning and on the thermal conditions of the process.

The second methodological step was the verification of the reliability of the secondary phase current measurements. Transformer ratios calculated from the measurement data were compared with the values resulting from the transformer characteristics and the actual operating tap positions. Since the primary-side power balance proved to be internally consistent, it was assumed that the secondary current measurements were affected by error. As a result, a systematic underestimation of electrode currents by approximately 10% was identified. Correction coefficients of k_1 = 1.104, k_2 = 1.102, and k_3 = 1.049 were introduced, which yielded corrected average currents of 31.180 kA, 34.961 kA, and 29.722 kA, respectively. After application of this correction, it became evident that all electrodes operated above the rated current of the transformer and that the overload of the central electrode was substantially higher than indicated by the raw measurement data. The calculated correction coefficients are presented in Table 2.

In the third step, the theory of physical similarity of furnaces was applied [12, 14, 16, 17]. A 20 MVA reference furnace equipped with electrodes of 1200 mm diameter was adopted as the reference system. For the 7.75 MVA furnace, electrodes of 900 mm diameter were considered, as well as, for comparison purposes, electrodes of 850 mm diameter, i.e., the diameter originally specified in the design of these furnaces. Three similarity criteria were employed: the ratio of useful powers, the ratio of electrode diameters, and the ratio of electrode currents. On this basis, scaling relationships were determined for active power, bath resistance, phase current, and phase voltage. In these calculations, the power factor and electrical efficiency values determined from the measurement data were adopted, assuming that symmetrization of the system itself would not significantly alter them.

Table 2. Correction of electrode currents based on the transformer ratio

Electrode	Tap [V]	Primary current I1 [A]	Secondary current I2 [kA]	Transformer ratio z'	Correction coefficient k	Corrected current I'2 [kA]	Remark
1	136	684,116	28,239	41,308	1,104	31,180	Side electrode
2	136	766,022	31,712	41,371	1,102	34,961	Middle electrode
3	151,2	725,944	28,333	39,084	1,049	29,722	Side electrode

Results of the analysis

Actual Furnace Operating State

The statistical analysis showed that the furnace did not operate in a symmetrical three-phase regime during the analyzed period [23–25, 43]. The current distribution was distinctly asymmetrical, with the highest current consistently recorded in the central electrode. After correction of the systematic measurement error, the median current of the central electrode was 34.976 kA, whereas the other two electrodes operated at approximately 30 kA. The operating state of the furnace can therefore be described as a "2 × 30 kA + 1 × 35 kA" configuration rather than as a minor overload of a single phase.

This operating regime was associated with improved production performance. At these load levels, the specific electrical energy consumption for FeSi75 was approximately 8500 kWh/Mg, whereas under earlier operating conditions, when the load did not exceed 30 kA, it ranged from 8800 to 9200 kWh/Mg. This indicates a clear improvement in process efficiency under the present load distribution.

Results of the physical similarity analysis

The physical similarity analysis indicated that, for a 7.75 MVA furnace equipped with 900 mm diameter electrodes, two characteristic operating points correspond to proper thermal conditions in the reaction zones. For the 136 V tap position, the corresponding phase current is approximately 30 kA and the active power is about 5.3 MW. For the 151.2 V tap position, the corresponding phase current increases to approximately 35 kA and the active power to about 7.1 MW.

The present asymmetrical operating state of the furnace can be interpreted as a combination of these two operating points. If two electrodes operate at 136 V and approximately 30 kA, while one electrode operates at 151.2 V and approximately 35 kA, the resulting active power is approximately 5.89 MW. This value is in close agreement with the average active power determined from the operational data, i.e., 5.883 MW. The agreement between the physical similarity model and the industrial measurements indicates that the observed operating state is consistent with the predicted thermal operating conditions of the furnace.

Discussion

The results highlight a fundamental tension between electrical symmetry and technological optimum in six-electrode submerged arc furnaces. From the perspective of conventional electrical engineering, minimizing phase impedance asymmetry is generally regarded as desirable [13, 23, 24, 32]. However, in an electrothermal system such as the one analyzed here, this criterion cannot be considered independently of the thermal requirements of the process. Electrode immersion depth, local power release, and the thermal conditions in the reaction zones are all affected by relatively small differences in current distribution [4, 14, 16, 17, 20, 21, 23, 24].

The main finding of this study is that, under the investigated operating conditions, power supply asymmetry may perform a compensatory technological function. In the analyzed furnace, differentiated phase loading makes it possible to maintain thermal conditions closer to the process optimum than would be achievable under a formally symmetrical, but operationally constrained, configuration. The agreement between the corrected industrial data and the physical similarity analysis supports the interpretation that the observed asymmetrical operating state is functional rather than incidental.

This conclusion becomes evident when the feasible post-symmetrization operating variants are considered. Operation of all electrodes at 136 V would improve transformer operating conditions, but would reduce the achievable power and would therefore be unlikely to improve productivity. Conversely, operation of all electrodes at 151.2 V could increase furnace power, but only at the cost of severe overloading of all phases. An intermediate regime, combining higher voltage with lower current, would also be unfavorable because it would reduce electrode immersion depth and deteriorate thermal conditions in the reaction zones [4, 14–18, 26–29].

The results therefore indicate that simplified symmetrization of the high-current circuit is not technologically neutral. If introduced without a simultaneous increase in voltage-control flexibility, it may reduce the operating adaptability of the furnace and force the process into suboptimal operating states. This explains why improved formal electrical symmetry does not necessarily translate into improved process performance.

Operation above the nominal transformer current is, in practice, associated with the use of 900 mm electrodes instead of the originally designed 850 mm electrodes. The long-term tolerance of such overloads may be partly attributed to the conservative design of the existing 7.75 MVA transformers, although this does not eliminate the associated operational risk. From a practical point of view, this means that modernization should not be limited to geometrical symmetrization of the high-current circuit alone, but should also take into account voltage-control flexibility and transformer protection requirements.

Conclusions

The present study allows several conclusions of both scientific and practical significance to be drawn. At the same time, it should be noted that the analysis was based on data from one side of a single furnace and covered a limited operating period. Although the processed dataset comprised more than 10,000 measurement points, it still represented only a fragment of actual industrial operation. Moreover, the causes of the irregularities observed in the electrode current measurements require further clarification at the plant level. The conclusions should therefore be regarded as well supported, but still linked to a specific operating context. In addition, the modernization considered in this work was analyzed only as a simplified concept, and no full-scale industrial validation has yet been carried out. For this reason, the present study should be treated as analytical and prognostic rather than strictly validation-based.

The main conclusion of this work is that, in the investigated furnace configuration, asymmetry of the power supply system may perform a compensatory technological function. Under the analyzed operating conditions, differentiated phase loading makes it possible to maintain thermal conditions in the reaction zones that are closer to the process optimum than those achievable in a formally symmetrical but operationally constrained system.

1. The existing power supply system of the six-electrode furnace is characterized by significant phase impedance asymmetry resulting from the geometry of the short network and the linear arrangement of the electrodes. This asymmetry creates a natural tendency toward higher loading of the central electrodes and requires deliberate differentiation of phase operating parameters in order to maintain comparable electrode positions in the furnace.
2. The measured secondary electrode currents are underestimated by approximately 10%, which leads to underestimation of the actual overload conditions. After correction, two electrodes operate at approximately 30 kA, whereas one operates at approximately 35 kA, which means that all phases exceed the nominal current of the 7.75 MVA transformer.
3. The physical similarity analysis indicates that, for electrodes of 900 mm diameter, the optimum thermal conditions correspond to two characteristic operating points: approximately 30 kA at 136 V and approximately 35 kA at 151.2 V. The present operating state of the furnace can be interpreted as a combination of these two points and yields an active power consistent with the industrial operating data.
4. Simplified symmetrization of the high-current circuit, consisting solely in changing the arrangement of the water-cooled current-carrying tubes, does not guarantee an improvement in process performance. Operation of all electrodes at 136 V reduces the achievable power, whereas operation of all electrodes at 151.2 V requires severe overloading of all phases. An intermediate regime with lower current at higher voltage leads to less favorable thermal conditions in the reaction zones.
5. For this reason, modernization limited exclusively to high-current circuit symmetrization should not be regarded as a self-sufficient solution. Its practical justification depends on a simultaneous increase in voltage-control flexibility or on a more extensive reconstruction of the power supply system, including appropriate transformer protection measures.

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