A new Dimension of designing Arc Furnace High Current Systems

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Key words:
High current system, design optimization, Finite Network Method FNM, skin and proximity effect, 3D current density distribution, high accuracy computations
A new Dimension of Designing Arc Furnace High Current Systems.

Summary.

Badische Stahl-Engineering GmbH explores new ways of improved design of arc furnace high current systems. To date, the electrical design of arc furnace high current systems – especially current conducting electrode arms and transformer bustubes – is mainly based on experience and very basic electrical calculations.

BSE presents two innovative methods for the optimization of the high current system of arc furnaces:

- High accuracy computation of all electromagnetic effects for optimized design
- New Copper-Steel type electrode arms with flanged holder
Introduction.

At first glance the electric arc furnace seems to be a quite simple three phase unit. Three resistances in star connection, simple to calculate. In reality, the electric arc furnace is a highly complex system. The electrical quantities of the three phases are not constant, not sinusoidal, unsymmetric and closely coupled. All these are very undesired properties.

The extensive high current conductors with large cross sections are subject to current displacement, and the strong magnetic fields of the high currents negatively influence the system (induced voltages, eddy currents). To date, no exact physico-electrical calculation method for arc furnace problems exists. The conditions in the furnace and various other influences are too complex to solve with regard to the coupled equation systems of Maxwell, Navier-Stokes and mechanical equations that have to be considered. The arc voltages that provide best information of the arcs are not directly measurable. Common calculation methods for arc furnaces use e.g. the so called "operating reactance" and very simple models for reactance calculations that do not reflect the physical properties in and around the furnace.

BSE has decided to push forward the theoretical description of the electric of the arc furnace in a systematic, applicable and innovative way.

Precisely, this means to be able to accurately compute all electromagnetic and dependent non-electromagnetic effects that occur in the high current system. The theoretical foundation to achieve this was developed by Prof. Farschtschi in form of the Finite Network Method (FNM). This method is an innovation. BSE now applies it successfully on arc furnaces.

The “new dimension” mentioned in the title indicates that the computer aided optimization can start – similar to most fields in physics and electrical engineering. Just 10 years ago, this would not have been possible using a standard workstation due to other solution methods and the involved large linear equation systems. In the following it will be pointed out what the new dimension precisely means.
The Finite Network Method FNM.

The Finite Network Method FNM is a very consequent and smart application of Maxwell’s electromagnetic theory. It generally solves the – mathematically and physically – extremely difficult problem of the spatial current displacement (3D skin and proximity effect, eddy current problem) considering ferromagnetic material like steel. The method can be applied universally, it is not just limited to the arc furnace. But for this it is the perfect solution!

The foundation for solving all electrical problem of the high current system is the knowledge of the current density distribution inside the extensive conductors with large cross sections. All other electrical and also non-electrical quantities like forces or heating can be computed on this basis (locally and/or globally). The current density distribution is extremely inhomogeneous. A difference of magnitude of 1:100 with regard to the whole high current system is normal (depicted in figures 2 to 8).

This fact is important as for example one characteristic quantity of the EAF, the short circuit impedance of the high current system, depends on the current density distribution and on the geometry. Common computation methods assume constant current density everywhere – a simplification that is unrealistic obviously. FNM even provides the basis for a realtime measurement of the real arc voltages by accurate computation of all position dependent inductances of the high current system.

The accuracy of the FNM solution is only depending on the modelling of the conductors. The better reality is reproduced, the better the spatial discretisation is, the better the result. The algorithms are analytic and therefore always exact. The computation is only carried out for conductors leading current (if required for conductive, also ferromagnetic parts of the furnace periphery like structures with induced eddy currents). A huge advantage with regard to accuracy and computation time compared to common Finite Element or Finite Difference methods that require a large but empty space volume to be considered.
Arc Furnace Application.

At the electric arc furnace, there is a number of quantities that are of interest for the optimal design of the high current system (new installations or revampings):

- Determination, respectively prevention of hot spots in the high current system. These occur due to locally excessive current density in the conductors or due to induction in peripheral, conductive (also ferromagnetic) parts of the furnace. Using FNM, the current density can be computed at every point of the conductors. The results: Increase of material lifetime, material savings respectively optimal material size (e.g. copper shell), optimal cooling.

- Determination, respectively prevention of excessive heating in metallic parts of the furnace structure caused by induced eddy currents. This affects e.g. stools, masts, gantry arms and other structural parts. Result: prevention of damages or leakages caused by excessive heating.

- Optimization of the design (geometry) of the high current system for minimal unsymmetry. Determination of the current load in single high current cables and of design measures how to balance the currents in a cable-bundle or delta closure. Accurate calculation of short circuit impedances. Straining short circuit tests (dip tests) are already unnecessary. Results: optimal power input over the whole heat, increased cable lifetime.

- Computation of the appearing electro-dynamic forces and momenta on masts, arms, cables, electrodes and steel bath. Reliable results for the design of masts and guiding rolls, optimized mechanical design, reliability, cost savings.

- Computation of the magnetic field strength around the furnace, e.g. inside the operator control room. The effect of shielding is considered. Determination of the exposition of personnel due to alternating magnetic fields.

- Realtime measurement of the arc voltages based on the accurate calculation of inductive coupling of the three-phase system. Use of the arc voltages as regulator control variables. Optimized power input and improved regulating behaviour.

- Consideration of the additional effects of ferromagnetic materials like steel. This concerns especially electrode arms made of copper and steel, either copper plated or in the new BSE design with copper shell. Analytical comparison of aluminium arms with Cu-St-arms and of Cu-St-arms of different design among each other. Optimal design.
Conductive Electrode Arms with new Design.

To date, current conductive electrode arms are made in two variants. Since 25 years BSE offers the proven electrode arms with flanged holder made of pure aluminium alloy. These have been continuously operated at Badische Stahlwerke BSW. The other variant are copper plated steel arms. The copper skin that leads almost all the current is firmly attached to the steel surface. The plating can lead to problems if the copper is too thin or if the cooling is insufficient. Then detachments can occur. A flanged design has not been introduced to date.

BSE has developed a new design for conductive electrode arms with steel body and flanged holder. This design does not rely on copper plating but on a separate copper shell which surrounds the steel body with a certain gap. The shell is suitably welded to the steel body. The cooling water flows inside the gap between steel and copper.

The advantage of this design is the very direct cooling of the current carrying copper surface. Applying FNM, the copper shell is optimised to avoid locations with excessive current density and the optimal water cooling is determined.

A prototype with flanged holder was in continuous operation at BSW’s furnace No. 2 for one year (2014). It has proven its reliability, no problems occurred.

Figure 1 depicts the appearance of typical BSE copper shell arms. The weldings for the connection of copper and steel are visible. The impedance of this kind of arms (and the others respectively) can be accurately computed using FNM. The evaluation of the differences between the three types of conductive arms is an interesting future task that only FNM can solve.

Figure 1: New BSE copper shell conductive electrode arms with flanged holder
Exemplarily, the high current system of BSW’s furnace No. 1 has been modelled in good approximation, e.g. using ropefunctions for the cables. The figures 2 to 8 depict the current density distribution of the high current system for a relatively rough discretisation level. However, the significant properties become clear. A more refined discretisation is of course feasible but requires more computation time. Presently the computations run on a workstation with two Xeon CPUs with 10 real and 10 virtual cores each. Parallelisation is a vital requirement for fast computation times of some hours.

The computation results clearly show the very inhomogeneous current density distribution inside the conductors, especially the variation along the axes.

Figure 2 depicts the current displacement towards the edges of the arms and indicates the high load of the cable connections. Compared to the upper parts of the electrodes, the difference in current density magnitude is of order 1:100.

**Figure 2:** Inhomogeneous current density distribution in the high current system, top view
Figure 3 depicts the arms from below. The areas with high load are obvious. Compared to the top view, it can be seen that the current is taking the shortest way – the one at the bottom.

**Figure 3:** Inhomogeneous current density distribution in the high current system, bottom view

Figure 4 depicts the very inhomogeneous current density distribution at the external delta closure of the transformer. Local differences are of order 1:5 up to 1:10.

**Figure 4:** Inhomogeneous current density distribution in the transformer delta tubes
Figure 5 similarly depicts the very inhomogeneous current density distribution in the high current cables. Here too, current density differences of order 1:10 can be found. The inner sides of a cable bundle show much less current density than the outside of the bundle.

Figure 5: Inhomogeneous current density distribution in the high current cables depicted in a cross-section (red: 8A/mm², green: 4A/mm², purple: close to zero)

Figures 6 and 7 depict the situation inside the graphite electrodes. Clearly visible is the proximity effect and the current displacement outwards (skin-effect). The current density differences are varying and are of order 1:2 over the length but of order 1:100 at the tip.

Figure 6: Inhomogeneous current density distribution in the electrodes depicted in a cross-section (left one is centre phase)

Figure 7: Difference in current density magnitude at the electrode tips is about 1:100 (blue:red)

Figure 8 eventually depicts the critical areas of the arm bodies showing a cross section. The current density differences are of order 1:5.

Figure 8: Inhomogeneous current density distribution in the arm bodies made of aluminium depicted in a cross-section (red: 5A/mm², green: 2.5A/mm², purple: close to zero)
Conclusion.

Valid for the optimal design of arc furnaces as well as for other areas of physics and electrical engineering is: only the possibility of accurate – that means local – computation of quantities leads to an optimal design.

The analytical comparison of dozens of alternatives becomes feasible with the computer. The practical side, respectively the experience side of the electric of the arc furnace finally gets a solid theoretical basis.

We at BSE have developed a far-reaching theoretical understanding of the electrical properties of the arc furnace and we will offer this additional and valuable knowledge as a computation service.

Applying the FNM-system it is feasible for the first time to compute all electromagnetical and the depending non-electromagnetical quantities considering the real geometry of the furnace.
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