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Calculation of electric arc furnace secondary circuit – analytical and numerical approach

Abstract. The paper presents the procedure of electric arc furnace secondary circuit calculations. The separate parameters that form the furnace circuit impedance have been determined. The operating current for given power factor has been calculated and verified. To get better insight of the operating conditions of the arc furnace, thermal and stress analysis of the secondary delta closure have been performed. The procedure and the results are verified by measurements over 110 tone electric arc furnace with rated power of 110MVA.

*Streszczenie. W artykule przedstawiono procedurę obliczeń obwodu wtórnego elektrycznego pieca łukowego. Zostały określone poszczególne parametry, które tworzą impedancję obwodu pieca. Między innymi został obliczony i zweryfikowany prąd przy danym współczynniku mocy. W pracy przedstawiono wyniki przeprowadzonej analizy termicznej i naprężeń w przypadku zwarcia obwodu wtórnego, wykonane celem lepszego zrozumienia warunków pracy pieca łukowego. Procedura i wyniki pomiarów zostały zweryfikowane przez pomiary w ponad 110 tonowym piecu łukowym o mocy znamionowej 110MVA. (**Obliczanie obwodu wtórnego elektrycznego pieca łukowego - podejście analityczne i numeryczne**).*

Keywords: electric arc furnace, power calculations, heat, stress
Słowa kluczowe: elektryczny piec łukowy, obliczenia elektryczne, ciepło, naprężenia.

Introduction

Electric arc furnaces (EAF) are electric process heating systems that heat materials by means of an electric arc [1,2,3]. The modern EAF is a highly efficient recycler of scrap iron or other ferrous material used for making carbon and alloy steel. The electric arc furnace operates as a batch melting process producing batches of molten steel. Typically the batch cycle time is less than 60 minutes.

The EAF is one of the largest consumers of electrical energy in most of the power systems. According to the International Iron and Steel Institute (IISI) report [4] the annual crude steel production July 2016 versus 2015 reached almost 1 billion metric tons. Depending on the size of the furnace the amount of energy to produce one metric ton of steel is between 300 and 500 kWh. Having in mind that over 40% of the world steel is produced in electric arc furnaces it is not difficult to estimate the enormous quantity of electrical energy which goes into an electric arc furnaces process. This basic information clearly show that the necessity for reduction of energy cost, improvement of product quality and improvement of the process is more than required.

The electrical system in an EAF consists of a primary system which supplies power from the electrical utility and the secondary electrical system which steps down the voltage from the utility and supplies the power to the furnace. Typically, a furnace that ranges in size from 50-200 tones has transformer with rated power of 25-125 MVA, and electric energy consumption in the range from 440 to 400KWh/ton.

The main electric component of the EAF is the electric arc transformer (EAT), most commonly with 3 phases. The electrodes are connected to the secondary circuit of the transformer. The arc forms between the charged scrap iron and the electrodes, and the charge is heated both by current passing through the charge and by the radiant energy from the arc, as presented in Fig. 1 [5]. EAT is designed differently than the distribution transformers, mainly due to the heavy stress experienced by the unbalanced load during scrap melting. As such, the arc furnace transformer experiences sudden switching on and off, the secondary circuit is short circuited for extended period of time; the loads in the 3 phases are heavily unbalanced. These factors dictate more rugged design than the ordinary distribution transformer and consequently more specific calculation procedure.
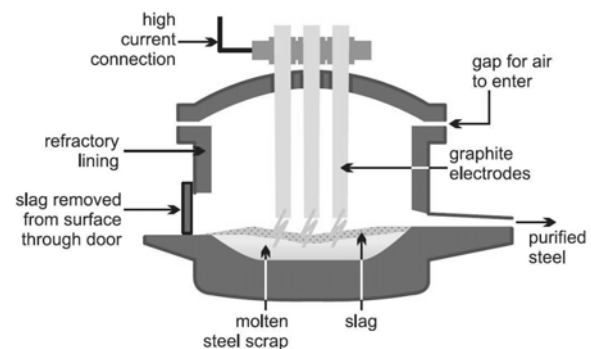

Fig. 1.electric arc furnace

In this paper the procedure of calculation of the electric circuit of EAF will be shown. Besides impedance components, the EAF operating power characteristics, stress and temperature will be calculated. The procedure will be based upon combination of analytical and numerical approach.

EAF electric circuit

The power flow from the utility's generators, through their network, arrives at the steel plant at very high voltage and must therefore be converted to low voltage suitable for the furnace arcs. Transforming the power from the kV level at the incoming utility line to the voltage level needed in the EAF is usually done in two stages. In the first stage a yard step-down transformer feeds several other transformers with-in the facility including the EAF transformer. A main breaker usually isolates all of the steelmaking facility's electrical systems from the power utility. This yard transformer steps the voltage down from the high-voltage line to a medium voltage level which is generally standardized for each country. In Europe this medium voltage is usually 30kV. From the 30kV busbar, the arc furnace is powered by a special, heavy-duty furnace transformer i.e. the EAT. The secondary voltage of this furnace transformer is designed to allow operation of the arcs in the desired range of arc voltages and currents. Since there are varying requirements of arc voltage/current combinations through the heat it is necessary to have a choice of secondary voltages. The furnace transformer is equipped with a tap-changer for this purpose. The main components that form the EAF electric circuit are shown in Fig. 2.
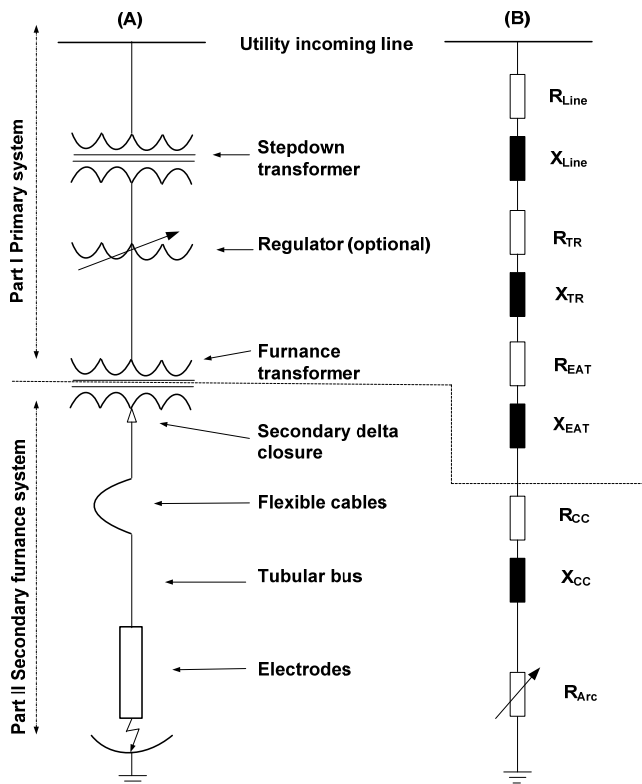
Fig.2. Equivalent electric circuit of EAF

The secondary circuit of the EAF electrical system consists of five major components: delta closure, flexible power cable, bus tube/conducting arm, electrode clamp/holder and the electrode, as shown in Fig.2. The secondary circuit of the EAF transformer terminates at low voltage bushings, which are attached to the delta closure, which consists of a series of copper plates, tubes or both. These are arranged so that the secondary windings of the transformer are joined to form a closed circuit. Most of this equipment is located within the transformer vault to assure a secure, clean environment.

The design arrangement of the secondary conductor group in modern EAF is equilaterally triangular, as in transmission line applications. With this arrangement the mutual coupling between the three phases is equalized and the unbalance in the resistance and reactance components is minimized. This electric circuit controls the operation of the furnace from electrical point of view. The transformer impedance, along with the impedance of the rest of the furnace electrical system determines the efficiency of the power supplied to the process.

Power calculations

To calculate the power characteristics the circuit impedance of the EAF and its resistance and reactance components has to be calculated first. Fig. 2(B) shows a single line diagram of the major resistance and reactance components that form the power system of electric arc furnace. Referring to Fig.2, there are five separate parameters to consider: These are:
- Utility line impedance $R_{line}+X_{line}$
- Step down transformer impedance $R_{TR}+X_{TR}$
- Electric arc transformer impedance $R_{EAT}+X_{EAT}$
- Secondary circuit impedance $R_{cc}+X_{cc}$
- Arc resistance R_{Arc}

The following data has been used for calculations:
- Utility short circuit rated power S_{line}=3000MVA at U_{line}=110KV;

- Stepdown transformer rated power S_{TR}=100MVA; 110kV/30kV; percentage impedance $Z_{TR\%}$=8%;
- EAT rated power S_{EAT}=100MVA ; percentage impedance $Z_{EAT\%}$=12,93%;

Secondary arc furnace circuit Rcc+Xcc=(0,6+j3,5) mΩ.

The secondary arc furnace circuit impedance has been found from short circuit measurements.

Impedance calculation

The 100MVA furnace transformer EAT has 21 tap positions. Position 21 ratio is 30kV/1154V. In the following example the calculations per phase were performed for tap position 15, being the most frequently used position during one batch. At this position the furnace voltage is stepped down to 946V. The circuit impedance components per phase that have to be accounted are as follows:
- utility
- step down transformer
- electric arc transformer
- Secondary circuit $Z_{cc}=(0,6+j3,5)10^{-3}\Omega$/phase

The rated impedance to 946V reference voltage has been calculated:
- utility (110kV/946V) Z_{line}=0,298 mΩ/phase
- step down transformer (110kV/946V) Z_{TR}=0,716 mΩ/phase
- electric arc transformer (30kV/946V) Z_{EAT}=1,157 mΩ/phase

Table 1 gives a summary of the circuit impedance components, referenced to secondary furnace voltage of 946V.

Table 1. Circuit impedance components

Circuit component	resistance (mΩ/phase)	reactance (mΩ/phase)	impedance (mΩ/phase)
Utility	0.00295	0.29651	0.298
Step down transformer	0.08735	0.70877	0.716
Electric arc transformer	0.14117	1.14556	1.157
Secondary circuit	0.60000	3.50000	3.551
Total	0.83147	5.65114	5.712

To break the circuit impedance to vector components the following X to R ratio has been used [6]:
- For the utility impedance X/R=10/1, therefore the phase angle is 84,29°
- For the step down transformer impedance X/R=8/1, therefore the phase angle is 82,87°.

The effect of harmonic distortion increases the total system reactance for 10%, while the resistance increases due to eddy current for 10%. Therefore the total short circuit impedance has been found:

$$(1) \qquad Z_{tot} = R_{tot} + X_{tot} = (0,914 + j6,216)\ (m\Omega)$$

Operating current calculation

The power factor of the electric arc furnace circuit changes from the infinite bus to the tip of the electrodes. The arc under any operating circumstances is purely resistive and its power factor equals 1. Power factor above 0,85 is considered as unstable arc region, while for power factors below 0,65 the power losses get too high. When operating a furnace with equal active and reactive power, the power factor is 0,707 and maximum circuit power is transferred into system. This operation mode is known as maximum efficiency. Maximum productivity is obtained for somewhat higher power factor, and for the given calculation average power factor of 0,72 has been assumed.

In this case the operating resistance is:

$$(2) \qquad R_{op} = \sqrt{\frac{PF^2(X_{tot} - X_{line} - X_{TR})}{(1-PF)^2}} \ (m\Omega)$$

where: R_{op} - total operating resistance in $m\Omega$, PF - operating power factor, X_{tot} –total operating reactance, X_{line} – utility reactance and X_{TR} – EAT reactance.
   The operating impedance is:

$$(3) \qquad Z_{op} = \sqrt{R_{op}^2 + X_{tot}^2} \quad (m\Omega)$$

The secondary operating current is:

$$(4) \qquad I_{op} = \frac{946}{\sqrt{3} \cdot Z_{op}} \quad (kA)$$

The calculated secondary circuit impedance and current are shown in Table 2.

Table 2.Operating furnace calculated values

R_{op}(mΩ/phase)	resistance	5.40
Z_{op}(mΩ/phase)	impedance	8.24
I_{op}(KA)	secondary current	66.30

   The calculated results comply with the data given on the transformer name plate for the tap position 15. Rated current for position 15 is 61,031kA while measured current is 60kA.The calculated secondary current is somewhat bigger than the actual measured current due to the fact that calculations have not accounted the positive temperature coefficient of the operating resistance.

Delta closure conductors calculation
   Power exits the furnace transformer via low voltage bushings which are connected to the delta closure. In this example the delta closure consists of 6 copper plates per bushing i.e. 36 rectangular copper plates per phase. These are arranged so that the individual secondary windings of the transformer are joined to form a closed circuit. The delta closure is contained in the transformer chamber and protrudes through the vault wall to connect with the power cables. Heat transfer and stress calculations have been performed for this part of the secondary circuit.

Temperature calculations
   The temperature distribution of the delta closure conductors per phase have been calculated numerically, as coupled problems solution. The volume power of the heat source q_g=63206W/m^3 has been calculated as DC conduction problem and further exported to the steady state heat transfer solution. In the heat transfer problem thermal conductivity of the copper plates has been set to k=401W/Km. Convective boundary condition has been set on the outer surfaces of each copper plate.
   Figure 3 shows temperature distribution for 2 of the outer, and the 2 inner copper plates, when the ambient temperature is set to 40°C.
   The calculated temperatures in the copper plates are shown in Table 3.

Table 3. Temperature of the copper plates for given ambient temperature

Ambient temperature[^{o}C]	Outer conductor temperature [^{o}C]	Inner conductor temperature [^{o}C]
40	80	80,8
60	99	100

Outer plate conductors
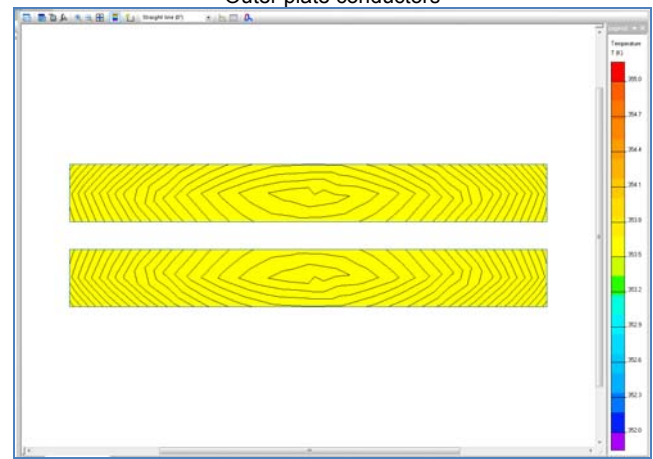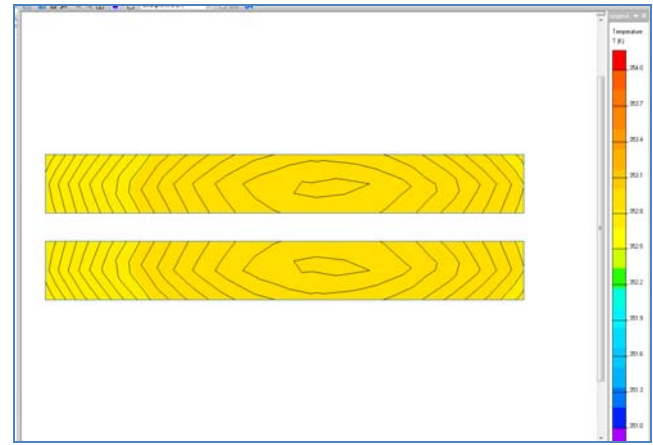
Inner plate conductors

Fig.3. Temperature distribution in the current conducting copper plates

Phase secondary current is:

$$(5) \qquad I_f = \frac{I_{op}}{\sqrt{3}} = \frac{663000}{\sqrt{3}} = 38324(A)$$

Phase current is divided into three equal currents in copper plates, therefore:

$$(6) \qquad I_{cp} = \frac{I_f}{3} = 12774(A)$$

Catalog current value [7] of selected cross section of copper plates is:

$$(7) \qquad I_{cat} = 16320(A)$$

Permissible current in each of the copper plates is obtained by multiplying the coefficient according to parallel running conductors.

$$(8) \quad I_{cat(per)} = 16320 \cdot k = 16320 \cdot 0{,}8 = 13056(A)$$

It follows that the current load requirement is satisfied and copper plates can permanently operate with rated current.

$$(9) \qquad I_{cp} = 12774(A) < I_{cat(per)} = 16320(A)$$

Stress analysis
   The high current plate conductors that form the delta closure can be exposed to high mechanical loads during operation. These loads are caused by the reaction of the conductors to the electromagnetic force. The maximum force is determined by the highest possible current peak which normally occurs under short circuit conditions.

For the given current plate dimension and shape, permissible mechanical stress according to [7] is:

(10) $\sigma_{cat(per)} = 170(MPa)$

Mechanical stress has been calculated analytically as in [6]:

(11) $\sigma_{cp} = 75,18(MPa)$

This result show that the mechanical stress is not exceeding the permissible stress and therefore the copper plates can permanently operate without being damaged.

(12) $\sigma_{cp} = 75,18(MPa) < \sigma_{cat(per)} = 170(MPa)$

Conclusions

As enormous quantity of electrical energy goes into an electric arc furnaces process, it is important to have clear insight of the arc furnace electric system with a goal of finding guidelines for saving energy and resources.

In this paper the impedance of the entire electric arc furnace system has been calculated. The operating current has been calculated for power factor that gives maximum productivity of the melting process. These calculations have been verified with available measurements.

Special emphasize has been given to the plate conductors that form the first part of the delta closure of the secondary circuit. Heat transfer analysis of delta closure copper plates together with the current load requirement has shown that these conductors can permanently operate with rated current. Also stress analysis confirmed that the copper plates can permanently sustain the mechanical forces between them.

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