SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 16, No. 2, June 2019, 181-193

UDC: 621.365.2:543.22/.23 **DOI: https://doi.org/10.2298/SJEE1902181C**

Electric Arc Furnace Transformer Secondary Circuit Calculations

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Abstract: This paper demonstrates a procedure for calculating stress and temperature in the secondary high current circuit of a modern electric arc furnace. At the beginning, the separate parameters that form the electric circuit from the furnace to the bushings of the electrodes are determined. The analysis of these parameters allows the selection of the optimum operational point of the furnace. Thermal and stress analysis of the transformer secondary delta closure is further performed. The procedure is given in detail with all the required equations and is illustrated on a real 110-ton furnace with a 110 MVA transformer.

Keywords: Electric arc furnace, Furnace transformer, Secondary circuit, Stress calculations, Temperature calculations.

1 Introduction

Electric arc furnaces (EAF) are electric process heating installations used for melting processes with the heat produced by an arc burning between the electrode and the charge. Typically, EAFs are used to produce carbon steels and alloy steels primarily by recycling ferrous scrap. The electrode voltages are typically in the range of 200–1500 V, while currents may reach several thousand amperes [1 − 4]. Bearing in mind that about 25% of world steel is produced in an EAF, the high value of arc furnace unit power and the high energy consumption makes EAF the most important electro-heating installations from both a technical and economical point of view. At the same time, they present one of the largest consumers of electrical energy in most power systems.

Since 1970, EAFs have continuously been technologically developed and improved, however their basic structure and principle of work remained significantly unchanged. In the past 50 years, the total energy required to melt the scrap was reduced from 580–650 to 320–350 kWh/ton [5], and the electrical energy share in the overall energy consumption dropped to 50%, while the electrode consumption was reduced by 4 to 5 times [4].

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The main electric component of the EAF is the step down electric arc transformer (EAT). Typically, EAT is three-phased and the graphite electrodes are connected to its high current secondary circuit. This furnace transformer is exposed to heavy electrical and thermal stress during normal operation, so it has a more rugged design compared to typical distribution transformers. The arc forms between the charge (the scrap iron) and the electrodes. The charge is then heated directly by the current flowing through it and, indirectly, by the radiant energy from the arc. Electric arc furnace processes and the steps of operation that go under tap-to-tap cycle are briefly explained in [2, 6].

The reliable and efficient operation of the EAF is dependent on reliable operation of the EAF transformer. Converting the furnace operation to higher power, increases productivity and reduces energy loss [7, 8]. Increased power can be achieved by installing new transformers and/or minimising the secondary circuit impedance. These modifications will change the circuit impedance components and, consequently, the EAF operating data. Any other modification of the electrical circuit in order to optimise or control the process will also affect the operating parameters of the EAF. All aforementioned situations require recalculation of the EAF impedance and operating characteristics.

The motivation for this work is to describe the procedure for calculation of an EAF and to verify it on a realistic case. Therefore, the equivalent electric circuit of the furnace is briefly explained and calculated. In the following part of the paper, the simplified stress and heat calculation equations are given. These equations are later applied to obtain mechanical stress and heat distribution in part of the delta closure copper plates of a 100 MVA EAT.

2 Arc Furnace Electric Circuit

Obtaining the furnace operating current is a complex task since it must take into account all the electric circuit impedance components, starting from the utility line and ending at the furnace electrodes. The aforementioned components have been calculated step-by-step. The operating current has been calculated for a power factor that gives the highest efficiency of the furnace.

2.1 Electric circuit components

The power from the incoming utility line is transformed to a low voltage level, required for the EAF melting process, in two stages. In the first stage, a yard step down transformer steps the voltage down from the high–voltage 110kV line to a medium 30 kV voltage level. From the 30 kV busbar, the arc furnace is powered by the furnace transformer. The EAT is equipped with a tap changer to allow operation of the arcs in the desired range of arc voltages and currents. The components that form the EAF electric circuit are shown in Fig. 1. In Fig. 1, the parallel transformer impedances representing core loss and the magnetising current are omitted, since generally the transformer magnetising current is considered as 4 to 5% of the full load current.

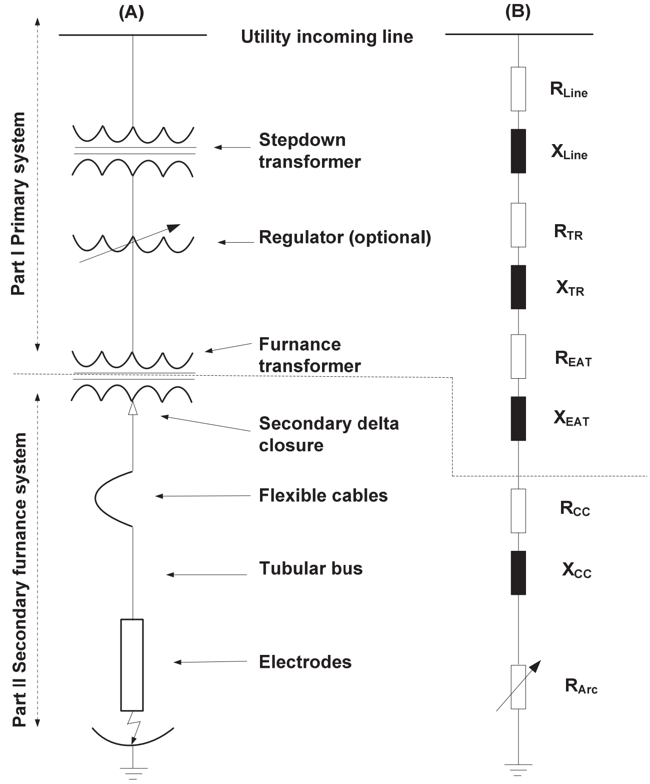


Fig. 1 – *Equivalent electric circuit of EAF.*

The secondary EAF system is the section of the electric circuit between the secondary terminals of the furnace transformer, i.e., EAT, and the arc bushings between the electrodes and the charge. Generally, the secondary EAF electrical system consists of seven major components: (1) three-phase transformer secondary, (2) substation busbars, (3) substation wall, (4) flexible cables, (5) delta connection bars, (6) high-current water-cooled bus tubes, and (7) contact pad and electrode clamping ring as shown in Fig. 2 [4]. In Fig. 2, the secondary circuit of the EAF transformer (1) terminates at the low voltage bushings, which are attached to the 3-phase copper delta closure and (2) the substation busbars. The delta closure and the busbars are arranged so that the secondary windings of the transformer are joined to form a closed circuit. They conduct the current from the transformer through a vault wall to the power cables.

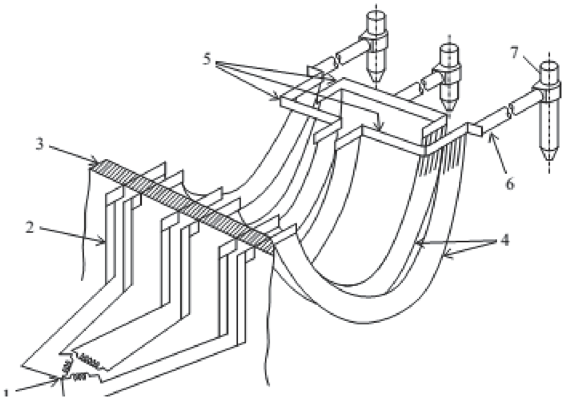


Fig. 2 – *Secondary high-current circuit.*

The secondary windings are connected in a triangle. This connection has the advantage of sharing, over two phases, the short−circuit current between two electrodes. At the same time, it gives the possibility to make the so-called two-wire reactance compensation with go and return anti-phase conductors, and to obtain, as much as possible, equal values of reactance in the three phases [9].

The design arrangement of the secondary conductor group (4, 5, 6, and 7 in Fig. 2) in the analysed furnace transformer is presented in Fig. 3. This arrangement is similar as in transmission line applications and contributes to reduction of the phenomena “transfer of power” from one phase to another [4, 9].

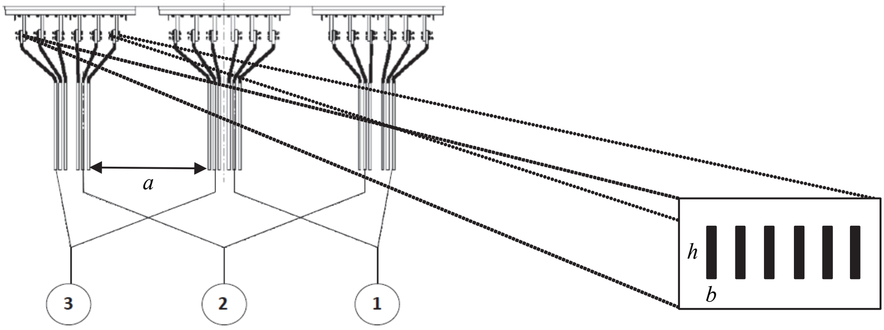


Fig. 3 – *Design arrangement of the secondary conductor group*.

The enlarged fragment in Fig. 3 presents the arrangement of the copper plate conductors per low voltage bushing. As shown, there are six copper plates per bushing with a rectangular cross section of the dimensions of b = 12 mm and h = 100 mm.

2.2 EAF electric circuit parameters

The EAF that is subject of analysis has a step down 100 MVA furnace transformer with 21 tap positions. The position 21 ratio is 30 kV/1154 V. For tap position 15, being the most frequently used position during one batch, the furnace voltage is stepped down to 946 V. This voltage delivers maximum megawatt power at optimum current, providing good arc stability, i.e., enhanced steel quality, improved power factor, and reduced electrical losses. In this example, the delta closure consisted of 6 copper plates per bushing and contains 36 rectangular copper plates per phase. The circuit impedance components that form the electric circuit as shown in Fig. 1, have been calculated following the procedure given in [3, 10, 11].

Referring to Fig.1, there are five separate parameters to consider:

- 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 $R_{CC} + X_{CC}$, and
- Arc resistance R_{arc}.

The following data has been used for calculations:

- Utility short circuit rated power $S_{line} = 3000\,\text{MVA}$ at $U_{line} = 110\text{ kV}$,
- Stepdown transformer rated power $S_{TR} = 100\,\text{MVA}$, $110\text{ kV}/30\,\text{kV}$; percentage impedance $Z_{TR\%} = 8\ \%$,
- EAT rated power $S_{EAT} = 100\,\text{MVA}$ and percentage impedance $Z_{EAT\%} = 12.930\ \%$, and
- Secondary arc furnace circuit $R_{CC} + X_{CC} = (0.600 + \text{j}3.500)\,\text{m}\Omega$. This impedance has been found from short circuit measurements.

2.3 Impedance per phase calculations

Utility impedance:

$$Z_{line} = \frac{U_{line}^2}{S_{line}} = 4.033\,[\Omega/\text{phase}]. \tag{1}$$

Step down transformer impedance:

$$Z_{TR} = \frac{Z_{TR\%} U_{TR}^2 \cdot 10}{S_{TR} \cdot 10^3} = 9.680\,[\Omega/\text{phase}]. \tag{2}$$

Electric arc transformer impedance:

$$Z_{EAT} = \frac{Z_{EAT\%} U_{EAT}^2 \cdot 10}{S_{EAT} \cdot 10^3} = 1.164\,[\Omega/\text{phase}]. \tag{3}$$

2.4 Rated impedance to reference voltage calculations

Using (4), the aforementioned impedances per phase have been recalculated to reflect the reference voltage of 946 V:

$$Z' = Z\left(\frac{E_2}{E_1}\right)^2. \tag{4}$$

In (4), Z is the corresponding impedance using (1), (2), and (3) and Z' is the recalculated referenced impedance. The referenced utility impedance is:

$$Z'_{line} = 0.298[\text{m}\Omega/\text{phase}]. \tag{5}$$

The referenced step down transformer impedance is:

$$Z'_{TR} = 0.716[\text{m}\Omega/\text{phase}]. \tag{6}$$

The referenced electric arc transformer impedance is:

$$Z'_{EAT} = 1.157[\text{m}\Omega/\text{phase}]. \tag{7}$$

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

Table 1
Circuit impedance components.

Circuit component	resistance [mΩ/phase]	reactance [mΩ/phase]	impedance [mΩ/phase]
Utility	0.003	0.296	0.298
Step down transformer	0.087	0.709	0.716
Electric arc transformer	0.141	1.146	1.157
Secondary circuit	0.600	3.500	3.551
Circuit impedance	0.831	5.651	5.712
Total circuit impedance	0.914	6.216	6.282

To break the circuit impedance into vector components, the following *X* to *R* ratio has been used [3]:

- For the utility impedance $X/R = 10/1$, therefore, the phase angle is 84.29 degrees, and
- For the step down transformer impedance $X/R = 8/1$, therefore, the phase angle is 82.8 degrees.

To account for the effects of harmonic distortion and eddy currents, the circuit impedance is increased by 10% [3]. The last row in **Table 1** shows the total EAF resistance and reactance that is used for further calculation.

2.5 Operating current calculation

The active power is controlled through the variation of the arc length that directly influences the power factor. As a general rule, maximum active power is transferred into the system when the power factor is 0.707 and, in such case, the EAF works with highest efficiency. On the other hand, maximum productivity is obtained for somewhat higher power factors than the aforementioned. In this analysis, maximum productivity is obtained for an average power factor of 0.720 per batch. This power factor has been determined from the analysis of a circle diagram as explained in [4] and verified in practice. In this case, the operating resistance is:

$$R_{op} = \sqrt{\frac{PF^2 (X_{tot} - X_{line} - X_{TR})}{(1-PF)^2}} \, [\mathrm{m\Omega}], \tag{8}$$

where R_{op} is the total operating resistance in m**Ω**, PF is the operating power factor, X_{tot} is the total operating reactance, X_{line} is the utility reactance and X_{TR} is the EAT reactance.

The operating impedance is:

$$Z_{op} = \sqrt{R_{op}^2 + X_{tot}^2} \, [\mathrm{m\Omega}]. \tag{9}$$

The secondary operating current is:

$$I_{op} = \frac{946}{\sqrt{3} Z_{op}} [\mathrm{kA}]. \tag{10}$$

For 0.720 average power factor per batch, the calculated secondary circuit impedance and current are shown in **Table 2**. In this case, the calculated rated current for position 15 is 66.300 kA. The calculated results comply with the data given on the transformer name plate for tap position 15. In these calculations, the increase of resistance with temperature has not been taken into account.

Table 2

Operating furnace data – calculated versus declared.

		Calculated	Declared
Resistance	R_{op}[mΩ/phase]	5.403	6.400
impedance	Z_{op}[mΩ/phase]	8.243	8.950
secondary current	I_{op}[KA]	66.305	61.300

3 Stress and Heat Calculation of the Sub-station Delta Closure

In the next section, mechanical and heat stress is calculated for selected parts of the high current circuit, i.e., for the rectangular copper plates that are shown in the fragment in Fig. 3. These plates are part of the three−phase secondary delta closure.

3.1 Mechanical stress in the copper plates

Normally, during one batch, the EAT experiences frequent short circuit currents of about 2.5 to 4 times the rated current [4]. The magnitude of the forces generated by these high currents may cause deformation of the bars and failure of mountings. Therefore, it is important to know the stress experienced by the copper plates. The calculation of the short circuit line current is done assuming the worst case of a 400% increase in the operating current. Therefore, the line short circuit current is:

$$I_k = 4I_{op} = 265200\,[\mathrm{A}]. \tag{11}$$

According to the geometry presented in Fig. 3, the short circuit current per phase per copper plate (note that there are six plates per bushing) is:

$$I_{kphase} = \frac{I_k}{\sqrt{3}}\frac{1}{3\cdot 6} = 8516\,[\mathrm{A}]. \tag{12}$$

The corresponding peak current in such case is:

$$I_{peak} = \sqrt{2}I_{kphase}(1+\mathrm{e}^{-t/T_k}). \tag{13}$$

In (13):

$$t = T/2 = 0.010\,[\mathrm{s}] \tag{14}$$

and

$$T_k = \frac{X_k}{\omega R_k}, \tag{15}$$

where:

$$X_k = X_{cc} + X_{EAT} = 4.645\,[\mathrm{m\Omega}] \tag{16}$$

and

$$R_k = R_{cc} + R_{EAT} = 0.741\,[\mathrm{m\Omega}] \tag{17}$$

Hence:

$$T_k = 0.020\,[\mathrm{s}]. \tag{18}$$

Substituting (11), (14) and (18) in (13) the peak current has been calculated:

$$I_{peak} = 27396\,[\mathrm{A}]. \tag{19}$$

The force experienced by the copper plate is:

$$f = \sqrt{3} \cdot 10^{-7} \frac{1}{a} I_p^2 = 112\,[\mathrm{N/m}], \tag{20}$$

where a is the central distance between the copper plates from different phases (see Fig. 3) and, in this case, is assumed to be 1.16 m.

The mechanical stress per phase per copper plate has been calculated as:

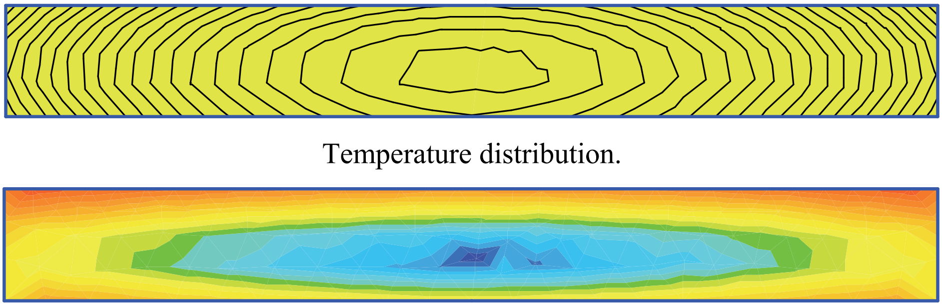
$$\sigma = \frac{fL^2}{hb^2/6} = 29.862\,[\mathrm{N/mm^2}] = 29.862\,[\mathrm{MPa}]. \tag{21}$$

In (21) the copper plate height is h=10 cm and the copper plate width is b=1.200 cm. The distance between two points of fixing on the same phase copper plate (distance from the transformer to the wall) is L=0.800 m.

The typical stress of copper ranges between 170 and 200 MPa [12]. In this example, the copper plates are experiencing lower levels of stress than the one that can be sustained by the material.

3.2 Temperature calculation in the copper plates

The copper plates, shown in the fragment of Fig. 3, are heated by the power dissipated in them by the load current flowing through the resistance and cooled by radiation to its surroundings and convection from its surfaces. The ambient temperature in the chamber is assumed to be 40°C, i.e., 313 K.



Temperature distribution.

Heat flux

Fig.4 – *Temperature distribution and heat flux in the copper plates.*

The temperature distribution of the delta closure conductors per phase has been calculated numerically as a coupled problem with a procedure given in [11]. The current flowing in each of the copper plates defines a volume power of the heat source of $q_g = 63.206$ W/m^3. In the calculations, the thermal conductivity of the copper plates has been set to $k = 401$ W/Km [13]. A convective boundary condition has been set on the outer surfaces of each copper plate. The ambient temperature is set to 313 K. The temperature distribution and the heat flux in one of the outer plates are presented in Fig.4. The numerical results show that the temperature in each of the six copper plates did not exceed 353 K (80°C), while the heat flux maximum was 488 W/m^2. The slight asymmetry of the field isotherms is due to the better cooling conditions on the edge that is not next to another copper bar.

3.3 Calculation of permissible operating current

The permissible operating current per copper plate has been calculated analytically using two approaches. The first approach is straightforward and uses empirical relations. In the second approach, the transferred heat from the conductor plate is assumed.

3.3.1 Empirical approach

The secondary current per phase is:

$$I_f = \frac{I_{op}}{\sqrt{3}} = \frac{66300}{\sqrt{3}} = 38324\,[\mathrm{A}]. \tag{22}$$

This current divides into three equal currents in the copper plates, so:

$$I_{cp} = \frac{I_f}{3} = 12774\,[\mathrm{A}]. \tag{23}$$

The catalogue current value [12] for the aforementioned rectangular cross section of the copper plates is:

$$I_{cat} = 16320\,[\mathrm{A}]. \tag{24}$$

The permissible current in each of the copper plates is obtained by multiplying the catalogue value I_{cat} with the coefficient $k = 0.800$ that is used for parallel running conductors:

$$I_{per} = 16320k = 16320 \cdot 0.800 = 13056\,[\mathrm{A}]. \tag{25}$$

With this approach, the current load requirement is satisfied and the copper plates can permanently operate with the rated current:

$$I_{cp} = 12774[\mathrm{A}] < I_{per} = 13056\,[\mathrm{A}]. \tag{26}$$

Dividing (26) by 6, returns the permanent operating current per copper plate (I_p). In this example case, the operating current of 2129 A is below the catalogue value for the given cross section of 2176 A, as shown in (27):

$$I_p = \frac{I_{cp}}{6} = 2129\,[\mathrm{A}] < I_{per} = \frac{13056}{6} = 2176[\mathrm{A}]. \tag{27}$$

3.3.2 Heat transfer approach

The permissible operating current has been calculated once again with a simplified heat transfer approach as presented in [14]. The radiation heat transferred from the copper plate is:

$$q_z = 5.700 \cdot 10^{-12} \varepsilon (T_1^{\,4} - T_0^{\,4}) = 0.024 [\mathrm{W/cm^2}], \tag{28}$$

where $T_1 = 353\,\mathrm{K}$ and $T_0 = 313\,\mathrm{K}$ are the calculated plate temperature and room temperature, respectively. The emissivity ε of the plate is assumed to be 0.700, which is a typical value for a copper bar that has been in use for even a short time [13].

The convection heat transferred is:

$$q_k = 1.500 \cdot 10^{-4} (T_1 - T_0)^{1,350} = 0.020\,[\mathrm{W/cm^2}]. \tag{29}$$

Then the total transferred heat from one plate is:

$$q = q_z + q_k = 0.044\,[\mathrm{W/cm^2}]. \tag{30}$$

Each of the copper plates exchange heat with the area:

$$F = 2(b + h) = 22.400\,[\mathrm{cm^2/cm}]. \tag{31}$$

The ohmic resistance of the copper plate per unit length for a working temperature of 80°C is:

$$R = \frac{\rho}{S} = 1.725 \cdot 10^{-7} [\Omega/\mathrm{cm}] \tag{32}$$

with a 10% increase in the resistance due to eddy currents, the calculated resistance of one plate is:

$$R_a = 1.900 \cdot 10^{-7} [\Omega/\mathrm{cm}]. \tag{33}$$

Hence, the permissive operating current per copper plate is:

$$I_p = \sqrt{\frac{qF}{R_a}} = 2171\,[\mathrm{A}]. \tag{34}$$

Note that in equations (32 – 34), the resistance is the actual resistance of the copper plates and not the rated value.

Comparing (34) with (27), it is clear that both applied approaches return practically the same value for the permissible operating current.

4 Conclusion

The different operating modes of the EAF are characterised by the values of current, voltage, impedance, power, and power factor. These values strongly affect electrical efficiency, installation power factor, and utilisation coefficient of the furnace transformer. Therefore, it is especially important to use proper procedures for calculation of the aforementioned values.

This paper has presented the entire procedure for calculation of the operational parameters of the arc furnace high current secondary electric circuit. The referenced impedance components have been separately calculated from the utility to the step down transformer, the arc furnace transformer, and the secondary circuit. All the equations to calculate the separate parameters of the furnace transformer and the operating current, as well as heat and stress in selected parts of the high current circuit, are presented. The obtained numerical results are verified with the experimental results obtained on a realistic 110-ton EAF with a 110 MVA transformer.

The paper has also demonstrated a simplified method for calculation of stress and temperature in part of the secondary high current circuit of an electric arc furnace. The maximum force and temperature have been determined by the highest possible peak current, which normally occurs under short circuit conditions. The permissible current has been calculated using two approaches — empirical and simplified heat transfer approach. Both approaches give equal results confirming that they are equally applicable.

Having in mind that available similar works are mainly theoretical, these results make a contribution to the practical verification of the presented procedure. This procedure can be used as a useful guide for calculation of any EAF secondary circuit. Future work can include analysis of many parameters' effects on the EAF model.

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