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ELECTRIC-ARC-FURNACE PRODUCTIVITY OPTIMIZATION

OPTIMIZACIJA PRODUKTIVNOSTI ELEKTROOBLOČNE PEČI

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Štore Steel Ltd. is one of the largest producers of spring steel, forging steel and extra-machinability steel in Europe. Its electric-arc furnace (EAF) is one of the most important pieces of equipment in the steel plant. An EAF enables a plant to melt scrap as fast as possible with the maximum energy input. An electrical energy input depends on the secondary current and secondary voltage of the furnace transformer tap, influencing the electric-arc burning stability. The most influential EAF-transformer parameters (secondary current, secondary voltage, inductive resistance) have been optimized with the differential-evolution-algorithm method. The optimization results allowed a higher productivity (5 %), lower energy consumption (3.5 %) and lower productivity costs (8.7 %) achieved over a one-year period.

Keywords: electric-arc furnace, transformer, productivity, optimization, differential evolution

Štore Steel, d. o. o., je med največjimi proizvajalci vzmetnih jekel, jekel za kovanje in jekel z izboljšano obdelovalnostjo v Evropi. Elektroobločna (EOP) peč je najpomembnejši agregat v jeklarni. V EOP želimo pretaljevati jekleni odpadek čim hitreje, z največjim vnosom energije. Vnos električne energije je odvisen od sekundarnih napetosti in tokov v izbrani stopnji transformatorja peči, kar vpliva tudi na stabilnost gorenja električnega obloka. Najvplivnejši parametri napajalnega sistema (sekundarna napetost in tok, induktivna upornost) so bili predmet optimizacije z metodo diferenčne evolucije. Z uporabo rezultatov optimizacije smo dosegli višjo produktivnost (5 %), manjšo porabo energije (3,5 %) in manjše stroške proizvodnje (8,7 %) v opazovanem obdobju enega leta.

Ključne besede: elektroobločna peč, transformator, produktivnost, optimizacija, diferenčna evolucija

1 INTRODUCTION

Since its introduction, the EAF has been widely used in the metallurgy and smelting industries. An EAF working-point adjustment is the key factor in the efficiency of the EAF steelmaking. An AC EAF operation has a non-linear, time-varying behaviour. Because of this behaviour, the arc furnace creates harmonic pollution, voltage-flickering changes, frequency shifts and an unbalance of the three-phase system. These problems would severely affect the EAF productivity, the electrical-energy quality, the transmission efficiency and the equipment in a safe operation. An EAF process operation begins with charging the scrap steel into the furnace. Initially, the transformer voltage tap is kept at a low setting due to an instable arc burning when arcing to solid scrap. As the pool of liquid steel forming at the bottom of the arc furnace grows, the voltage setting and, hence, the power level can be increased due to a more stable arc behaviour. To reduce the problems caused by an instable arc burning, the following solutions are available:[1–3]

- decreasing the arc voltage,
- increasing the secondary (arc) current at the same secondary voltage,
- increasing the overall supply-system reactance.

Therefore, to deal with the problems of a reduced productivity, harmonic appearance and reduced flicker in an EAF supply system, this paper puts forward an approach for an optimally selected secondary (arc) current at each furnace-transformer voltage tap, with regard to the given ratio of the arc resistance to the overall supply-system reactance. For the new furnace-transformer secondary voltages, for each tap and stray, the reactance (its voltage drop) could be determined. The stray-reactance voltage drop could be in the range of 6–12 % of the nominal voltage depending on the design of the primary and secondary transformer windings.

The following steps were used:

- determination of the supply-network impedances, without the EAF transformer,
- determination of the arc impedances with regard to the arc-burning stability,
- determination of the EAF model,
- optimization of the EAF operation with regard to the supply-network impedances, the EAF arc impedance and the selected EAF model.

To determine the optimum secondary (arc) current and the furnace stray reactance at a given furnace-transformer secondary voltage, a simplified model of EAF was developed. The arc resistance was calculated according to the Cassie[4] equation and the arc reactance according to the Köhle[5] equation. The parameters from the simplified EAF model were used with a differential evolution algorithm in order to determine the optimum arc current and furnace-transformer stray reactance for each tap of the furnace transformer (the secondary voltage). For each transformer tap the maximum electrical power for the conversion is used for a particular length of the electric arc[3] and any deviation from this optimum length impairs the power-utilization efficiency.

In this paper the optimization results for each transformer tap are presented. Because of the optimization results, a higher productivity, lower operational costs and a lower energy consumption were achieved.

2 EXPERIMENTAL BACKGROUND

In general, there are several ways of operating an EAF and different ways of supplying the power. Basically, a more effective way of supplying the power depends on a number of restrictive facts, like the power-supply limitations, the EAF shell dimensions, the electrode configuration and the pitch-circle diameter. The electric-arc radiation on the refractory and water-cooled wall panels depends on the EAF shell diameter and the length of the arc (the arc voltage). In general, there are recommendations about the furnace-transformer apparent power per ton of liquid steel. A typical furnace-transformer power is up to 1.5 MV A/t of liquid steel. Another important parameter is the ratio between the arc resistance and the reactance of the supply network. In a modern design of an EAF supply network, the ratio should be near or below 1.5 in order to assure an acceptable impact of the EAF back on the electric-power-supply system. On the other hand, this ratio assures a stable arc burning in every state of the EAF. Regarding all the restrictions and recommendations, the arc-furnace-transformer secondary voltages have to be defined. Together with the secondary voltages, the arc resistance, the arc reactance and, consequently, the electric-arc burning stability are also defined. In addition, the transformer stray reactance and its voltage drop can be chosen when considering the furnace-transformer winding construction.

2.1 Determination of the supply-network impedances

The supply network (a connection from the point of common connection to the furnace transformer) uses an isolated neutral point. On the supply-network side there are the following limitations:

- the apparent power of the step-down transformer limited to 60 MV A,
- connection lines (4 × 3 × 1 × 300 mm^2, aluminum) and
- distribution center near the furnace transformer.

The supply-network impedances at the 110 kV and 35 kV voltage levels are converted, over the transformation ratio, to the secondary voltage level of the furnace transformer separately for each tap. The transformation ratio is defined for each tap of the furnace-transformer secondary voltage to its primary voltage. All the impedances are converted as follows:

$$Z' = Z \cdot \frac{1}{t_R^2}, \tag{1}$$

Z is the impedance of the device at its rated voltage,
Z' is the impedance of the device producing the furnace-transformer secondary voltage for each tap,
t_R is the transformation ratio.

The impedance at the point of common connection is defined as:

$$Z_{TM} = \frac{(c \cdot U_N^2)}{S_k''} \tag{2}$$

c is the voltage correction factor at the point of short circuit, $c = 1.1$
S_k'' is the symmetrical short-circuit apparent power.

The impedance of the 35 kV connection lines is based on the data from[6] and defined as $R_{35\ kV} = 0.1\ \Omega/km$ and $X_{35\ kV} = 0.18\ \Omega/km$ for one line. Actually, there are four parallel lines installed with a common length of 440 m:

$$Z_{35kV} = R_{35kV} + jX_{35kV} \tag{3}$$

The impedance of the step-down transformer is defined as:

$$Z_{SDT} = \frac{u_K \cdot U_N^2}{100 \cdot S_N} \tag{4}$$

According to[6] for a high-voltage apparatus, the resistance value being 10 % of the impedance can be defined as:

$$R_{SDT} = 0.1 \cdot Z_{SDT} \tag{5}$$

The reactance for the step-down transformer is defined as:

$$X_{SDT} = \sqrt{Z_{SDT}^2 - R_{SDT}^2} \tag{6}$$

According to equations (4), (5) and (6), the impedance, resistance and reactance for a furnace transformer can be defined in the same way. For the new furnace transformer the stray reactance and its voltage drop are not yet known. Therefore, just a range of the voltage drop (in fractions from 6 % to 12 %) caused by the stray reactance is given.

By now the impedances of the high-voltage supply network have been defined and converted into the secondary-voltage level for each tap of the furnace transformer. The impedances on the secondary side of the furnace transformer could not be measured. On the secondary side, there are the impedance from the high-current lines (short-circuit impedance) and the arc impedance. The measurements of the short-circuit impedances are made by diving two electrodes at the same time into the melt for a short period of time. Three measurements should be done each time with two different electrodes. At the time of the measurements, the furnace transformer should be set to the lowest voltage tap to prevent the secondary current of the furnace transformer from rising over the rated value. These measurement results are as follows:

$$Z_{\mathrm{SC}} = R_{\mathrm{SC}} + jX_{\mathrm{SC}} \tag{7}$$

2.2 Determination of the arc impedance

The arc impedance is explained with the arc resistance (the Cassie-Mayr arc model) and the arc reactance (the Köhle model). The Cassie-Mayr arc model successfully describes the key arc features as circuit elements.[7] The Cassie-Mayr arc model treats the arc resistance, R_{ARC}, as a dynamic variable, which is described as:

$$\frac{\mathrm{d}R_{\mathrm{ARC}}}{\mathrm{d}t} = \frac{R_{\mathrm{ARC}}}{\tau} \cdot \left(1 - \frac{U_{\mathrm{ARC}} \cdot I_{\mathrm{ARC}}}{P}\right) \tag{8}$$

Here, I_{ARC} is the current applied to the arc, U_{ARC} is the arc voltage, P is the typical power loss of the arc and τ is the time scale. As Cassie took the higher current in the arc column for his model, the Cassie equation can be used to determine the arc resistance. The electrical arc model can be described as a non-linear time-varying model. It can be described with the impedance that varies according to the scrap melting time in an EAF. The arc resistance can be represented with the Cassie equation without taking into account the complex physical processes of burning arcs. Assuming a constant temperature in the arc column, constant cooling by the entire volume and heat dissipation, the sinusoidal current and large time constants,[4] the following relation can be written:

$$R_{\mathrm{ARC}} = \frac{\sqrt{2} \cdot U_{\mathrm{ARC}}}{I_{\mathrm{ARC}} \sqrt{1 - \frac{\sin(2\omega t + \rho)}{1 + (\omega \vartheta c)^2}}} \tag{9}$$

where:

$$\vartheta c = \frac{Q}{P_{\mathrm{H}}} = 1, \text{ because of assumption } P_{\mathrm{H}} = Q \tag{10}$$

Q is the accumulated heat in the arc column,
P_{H} is the dissipated heat from the arc column,
U_{ARC} is the arc voltage between the cathode and anode,

$$U_{\mathrm{ARC}} = \frac{U_{12}}{\sqrt{3}} - \left(U_{\mathrm{kat}} + I_{\mathrm{ARC}} \cdot \sqrt{R_{\mathrm{SC}}^2 + X_{\mathrm{SC}}^2}\right) \tag{11}$$

I_{ARC} is the arc current in the arc column.

It is well known that an EAF has a lower active energy consumption than might be expected according to the calculated arc resistance. An additional reduction in the active power is caused by the arc reactance.[5] Arc reactance is caused by an electromagnetic induction (because of the non-linear and time-varying characteristic of the burning arc). The arc reactance defined by the Köhle model[5] is expressed as:

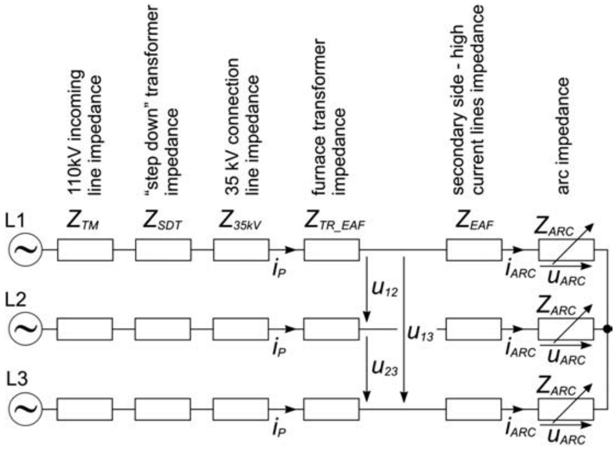

Figure 1: Equivalent-circuit diagram for an EAF
Slika 1: Nadomestno vezje elektroobločne peči

$$\frac{X_{\mathrm{ARC}}}{X_{\mathrm{SC}}} = K_1 \cdot \frac{R_{\mathrm{ARC}}}{X_{\mathrm{SC}}} + K_E \cdot \left(K_2 \cdot \frac{R_{\mathrm{ARC}}}{X_{\mathrm{SC}}} + K_3 \cdot \left(\frac{R_{\mathrm{ARC}}}{X_{\mathrm{SC}}}\right)^2\right) \tag{12}$$

where constants $K_1 = 0.08$, $K_2 = 0.13$, $K_3 = 0.04$ and time $T_{\mathrm{X}} = 18$ min are defined experimentally:

$$K_{\mathrm{E}} = e^{-\frac{t}{T_{\mathrm{X}}}} \tag{13}$$

For the EAF in Store Steel Ltd. the equivalent-circuit diagram is shown in **Figure 1**.

2.3 Determination of an EAF model

For an EAF model all the supply-network impedances, the arc impedance and secondary voltages for each tap of the furnace transformer are needed as the input data. From this data it is possible to determine all the necessary parameters of the EAF model. For a selected secondary-voltage tap and a given secondary current the furnace operating point can be calculated as follows:

$$U_{1\mathrm{S}}^{'} = t_{\mathrm{r}} \cdot (U_1 - I_{\mathrm{p}} \cdot Z_{\mathrm{p}}) \tag{14}$$

$$t_{\mathrm{r}} = \frac{U_{1\mathrm{zS}}}{U_{1\mathrm{zp}}} \tag{15}$$

$$I_{\mathrm{p}} = I_{\mathrm{S}} \cdot t_{\mathrm{r}}) \tag{16}$$

$$S_{\mathrm{S}} = \sqrt{3} \cdot U_1^{'} \cdot I_{\mathrm{S}} \tag{17}$$

$$P_{\mathrm{S}} = \sqrt{S_{\mathrm{S}}^2 - Q_{\mathrm{S}}^2} = \sqrt{S_{\mathrm{S}}^2 - (3 \cdot I_{\mathrm{S}}^2 \cdot X_{\mathrm{SC}})^2} \tag{18}$$

$$P_{\mathrm{ARC}} = P_{\mathrm{S}} - P_{\mathrm{SIZG}} = P_{\mathrm{S}} - 3 \cdot I_{\mathrm{S}}^2 \cdot R_{\mathrm{SC}} \tag{19}$$

$$R_{\mathrm{ARC}} = \frac{P_{\mathrm{ARC}}}{3 \cdot I_{\mathrm{S}}^2} \quad \text{or} \quad R_{\mathrm{ARC}} = \frac{\sqrt{2} \cdot U_{\mathrm{ARC}}}{I_{\mathrm{ARC}} \sqrt{1 - \frac{\sin(2\omega t + \rho)}{1 + (\omega \vartheta c)^2}}} \tag{20}$$

$$X_{\mathrm{ARC}} = R_{\mathrm{ARC}} \cdot K_1 + K_E \cdot K_2 \cdot R_{\mathrm{ARC}} + K_E \cdot K_3 \cdot \frac{R_{\mathrm{ARC}}^2}{X_{\mathrm{SC}}} \quad (21)$$

$$X'_{\mathrm{1SUM}} = t_{\mathrm{r}}^2 \cdot (X_{\mathrm{TM}} + X_{\mathrm{SDT}} + X_{\mathrm{35kV}} + X_{\mathrm{TR_{EAF}}}) \quad (22)$$

$$K_S = \frac{X_{\mathrm{SC}} + X'_{\mathrm{1SUM}}}{R_{\mathrm{ARC}}} \quad (23)$$

In addition to the secondary voltage, the EAF working point is also determined by the secondary current. The result of the criteria function is used to determine, at which EAF-transformer secondary voltage and current the arc burning is stable.

3 EAF OPERATION OPTIMIZATION

The differential-evolution method is a relatively new optimization algorithm that was presented by Price and Storn.[8] It is based on the origins of new populations in the evolution of mankind.

DE is the so called steady-state algorithm where new candidates do not compose an entirely new population but are simply added to the existing one. This method accelerates the convergence of the algorithm because the currently calculated quality individuals are immediately used for the new-candidate generation. In addition to the good convergence properties of DE, its algorithm is simple to understand and to implement. DE is also particularly easy to work with as it has only a few control variables that remain fixed throughout the entire optimization procedure.[8]

The following evolutionary parameters were selected for the process of simulated evolutions: 20 for the size of the population of organisms (*NP*), 50 for the maximum number of iterations, 0.8 for the crossover probability (*CR*) and 0.6 for the mutation factor (*F*). The crossover strategy of RAND/1/bin was selected.

A differential-evolution algorithm was run for each furnace-transformer voltage tap. The EAF-transformer secondary voltage and current should be chosen opti-

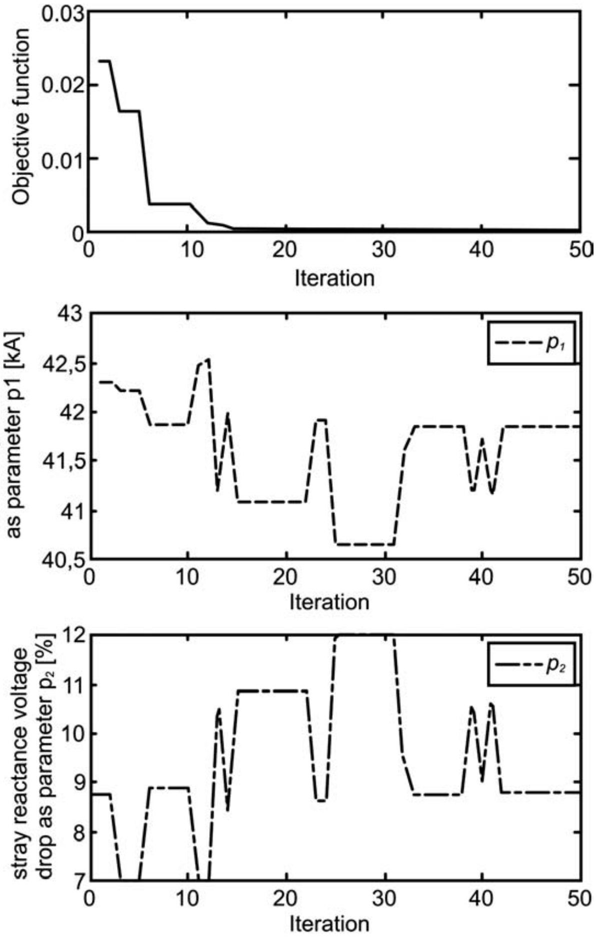

Figure 2: Differential-evolution iteration results

Slika 2: Rezultat iteracij algoritma diferenčne evolucije

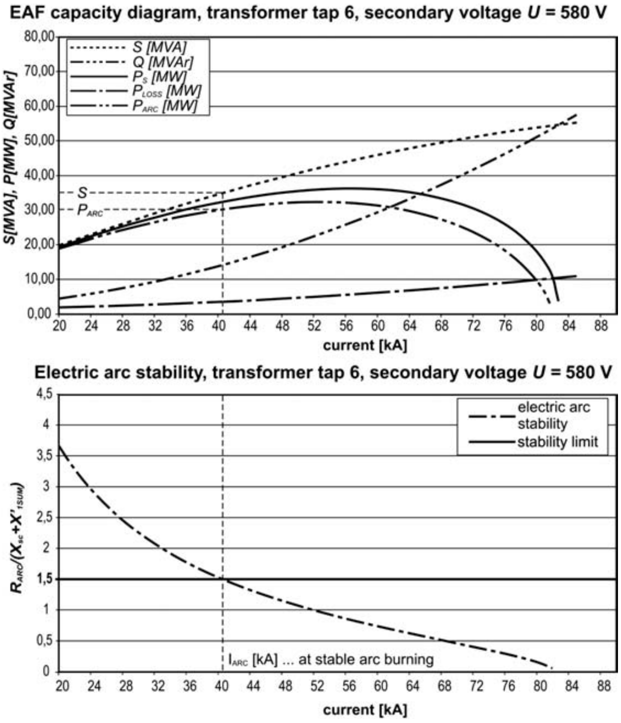

Figure 3: Capacity diagram for transformer voltage tap 6

Slika 3: Diagram moči za 6-napetostno stopnjo transformatorja

Table 1: Differential-evolution-method calculation results

Tabela 1: Rezultati izračuna z metodo diferenčne evolucije

Transformer voltage tap	Secondary voltage (V)	p_1/kA	p_2/%	Reactance (mΩ)
1	430	36.32	10.18	0.294
2	460	37.84	9.3	0.307
3	490	38.92	9.63	0.361
4	520	40.14	8.95	0.378
5	550	40.64	10.07	0.476
6	580	41.06	10.86	0.571
7	610	41.60	10.92	0.634
8	640	42.58	9.64	0.617
9	670	42.12	11.48	0.804
10	700	42.42	11.29	0.865
11	730	42.86	10.66	0.889

mally at a given ratio K_S (criteria function, equation 23). The secondary voltage and current at a given ratio K_S are optimal when the arc is burning stably, causing as little disturbance, voltage dips and asymmetry to the supply network as possible, whereby the EAF is at its most efficient operation and the melting of scrap is fast. As an example of a differential-evolution-algorithm result calculation, the results for furnace-transformer voltage tap 6 are shown (**Figure 2**).

For each transformer-voltage tap, optimization results using differential-evolution algorithm are shown in **Table 1**.

The differential-evolution optimization results for transformer voltage tap 6 can be presented as an EAF capacity diagram (**Figure 3**).

4 CONCLUSION

The overall energy intake to the EAF can be increased in two ways: by increasing the input of electrical power or/and increasing the intake of chemical energy. The EAF system has a very sensitive balance of its optimum operation. The furnace transformer should achieve these optimum values of the secondary voltage and current in order to have the highest possible electrical-energy input to the EAF, with minimum losses and consumption of all the other materials.

At the beginning, a determination of the supply-network impedances was performed. Afterwards the EAF arc impedance was determined with regard to the arc-burning stability. After the EAF-model selection, a differential-evolution algorithm was used for the optimization. An algorithm was run for each EAF-transformer voltage tap, and the calculation results of the stray reactance (or its voltage drop) and secondary current were determined for each transformer voltage tap. Also, a capacity diagram was plotted for each voltage tap. By installing a new furnace transformer, in comparison to the old furnace transformer, the following results were achieved:

- The tap-to-tap time was reduced from 90 min to 85 min (a 5.88 % shorter tap-to-tap time).
- The average daily production of the EAF has risen by 50 t of liquid steel (approximately 5 %).
- The consumption of electrical energy has been reduced by 3.5 %, from 450 kW h/t to 440 kW h/t.
- The consumption of the refractory material per year has been reduced, due to a higher productivity, from 4.25 EUR/t of liquid steel to 4.1 EUR/t of liquid steel (a reduction of 3.7 %).
- The consumption of other energy sources has also been reduced by 1.5 % per ton of liquid steel.

The outcomes of this paper relating to the EAF-transformer properties and a determination of the furnace working point at stable arc burning can be effectively utilized to enhance the productivity and reduce all the expenses during an EAF production.

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