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Procedia CIRP 48 (2016) 319 – 324

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23rd CIRP Conference on Life Cycle Engineering

# Energy efficient EAF transformer – a holistic Life Cycle Cost approach

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**Abstract**

As steel industry is a major energy consumer, huge improvements in EAF's energy efficiency has already been performed; thus, additional progresses are difficult. The main opportunity is to adopt a holistic approach considering all the relevant process components, especially the electric transformer, since all the melting energy pass through it. EAF transformers are exposed to more critical conditions than power transformers. The best solution should be designed evaluating the LCC: i.e. purchase, energy losses, cooling and maintenance costs. In the present work, a model and a numerical example are proposed to determine the total cost of ownership of EAF transformers.


Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering

*Keywords:* Transformer; EAF; LCC; cooling system; real losses; maintenance

## 1. Introduction

Steel production process consumes a huge amount of resources such as electrical and chemical energy (oxygen, natural gas, oil, carbon) and it is well recognized as one of the most energy-intensive process. Steel industry is one of the largest energy consumers in the manufacturing sector. Moreover, the energy consumption is expected to additionally increase: by 2050 steel use is projected to increase by 1.5 times to meet the needs of the growing population [1]. The production of primary steel is more energy intensive than the production of secondary steel due to the chemical energy required in reducing iron ore to iron using reducing agents. Consequently, electric arc furnaces (EAF), which are a common method of reprocessing scrap metal to create new steel, has acquired increasingly relevance through the years, especially for the higher competitiveness of the process. Aiming at improving efficiency and quality of the melting process, in the past decades huge improvements in terms of energy efficiency of the EAF have been introduced (see [2]), in order to: maximize stability of the arc during the different stages of the whole melting process;

- reduce electric disturbances (flicker) on the power supply network during melting process;
- increase productivity;
- reduce electrode consumption and optimize the cost of EAF equipment and of its operating costs.

Despite of the sophisticated energy management systems and the developments in terms of energy efficiency of the steelmaking process performed in the past decades, energy still represents a significant portion of the cost of steel production. Thus, further improvements in the process energy efficiency (and related reduction of production costs) will generate relevant savings and thereby improve the competitiveness. However, until the focus was mainly directed to the furnace, it was easy to get results, i.e. reduction of power off and tap-to-tap times, use of chemical energy, use of foamy slag, electronic regulation of the electrodes, higher voltage and use of reactors


Peer-review under responsibility of the scientific committee of the 23rd CIRP Conference on Life Cycle Engineering
doi:10.1016/j.procir.2016.03.045

in series, etc. The specific energy, mostly used today to melt a tonne of steel in an electric arc furnace, is virtually a parameter under control, very closed to the theoretical limit. Consequently, additional progresses without considering other components of the process are now difficult to be achieved as they have always been considered of secondary relevance. Thus, in order to improve the global efficiency of the process, the main opportunity is to adopt a holistic approach by including all the relevant parts. The main focus should be especially on the electric transformer, since all the power required for melting scrap, ferroalloys and other materials flows through it and its correct working is crucial for operations efficiency. Because of the relatively large capital expenditure involved when purchasing a transformer, most steelmaker are generally very well aware of the economic factors and savings that can be achieved at this stage of the transformer's life cycle. However, the other components of the total cost, which are not always taken seriously in industrial processes (e.g. costs due to energy losses and maintenance), represent a relevant share during the lifespan of the transformers. They can reach even the 70-90% of the lifetime costs and, thus, they should be considered in the purchasing decision. Consequently, the optimal transformer should be design evaluating the life cycle cost (LCC) taking into account all significant cost components and not only purchase price. Saving in quality only means postponing a capital expenditure to a future time. For that reason, companies' commitment is in investing in products of excellence that are tailored to meet the different requirements specific to every steel mill.

At the present, several study on the life cycle cost approach applied to the transformers have been performed ([3], [4]); however, all of them are focused on power and distribution transformers, while the steel making setting is not yet considered. Steelmaking process is characterized by severe conditions [5], such as EAFs requires dozen of interruptions a day and they are characterized by time-variant and non-linear loads. In addition, the instability of the arc creates relevant power quality problems such as unbalanced voltages and currents, voltage flickers as well as odd and even harmonics (due to the low voltage and high current AC power flow). Moreover, during the melting process, the melting iron sometimes causes shorts in the electrodes, which results in violent shocks to the power source. As EAF transformers are exposed to specific and more critical conditions than power/distribution transformers, it becomes crucial to consider real operating conditions and to extend the LCC approach to this specific context.

The present work has been developed in collaboration with Transformer Electro Service Srl. (TES), an important reality in high power and special transformers market, with a high specialization in the production of tailor made EAF transformer. The aim is to propose a LCC approach for EAF transformers: throughout the developed model it is possible to select the best design solution for the specific load cycle load and operating conditions, improving the energy efficiency of the global system and thus, increasing the energy transferred to the metal. Moreover, as an additional and relevant aspect introduced in the proposed model, the impact of real operating conditions and maintenance activity related to any single auxiliary component and equipment (e.g. smart cooling system, OLTC, etc.) have been included in the analysis.

## 2. LCC model for EAF transformer

Since EAF transformers operate connected to a system controlled by the operation of the furnace, they are subject to more critical conditions compared with power and distribution transformers: i.e. very high secondary currents and low secondary voltage, heavy current fluctuations and unbalanced conditions, switching transients, harmonics, short circuits, mechanical stress, frequent overloading conditions, vibrations, high ambient temperature, pollution and dust. For that reason, a holistic approach, which considers all the system components and not the only transformer, is necessary. Consequently, in order to achieve customer satisfaction, the challenge for suppliers is to design products that meet operation requirements, but at the same time they are reliable and cost competitive: such a goal can be reached by optimizing acquisition, ownership and disposal costs. A transformer with high efficiency and therefore low life-cycle cost would be expected to have low losses. In fact, since losses (in the form of heat) cause damage to the insulation over time, higher efficiency means a longer lifetime and reduced system degradation, i.e. lower failure rate. Moreover, a transformer with high efficiency reduces the amount of cooling power generation needed to accommodate the losses (both core and coil). Usually, EAF transformers are expected to operate about 20 years or more: thus, the procurement decision encompassing only the initial cost seems to be uneconomical. Since the transformer design affects all relevant performance, i.e. safety, reliability, maintainability, maintenance support requirements, etc., purchasing choice should be influenced not only by the product's acquisition price but also by the expected ownership cost, i.e. losses cost, cooling system cost and maintenance cost. Consequently, the analysis of the transformer costs over its lifespan through the life-cycle cost (also called "total owning cost") approach leads to a better economic evaluation. As stated in [6] and in accordance to IEC 60300-3-3 "Dependability management Part 3-3: Application guide – Life cycle costing" [7], the lifecycle of a product should consist of the following six cost-causing phases: (a) concept and definition, (b) design and development, (c) manufacturing, (d) installation, (e) operation and maintenance and (f) disposal. In order to develop an aggregated analysis, the different cost components can be grouped into investment or acquisition cost (concept/definition, design/development, manufacturing, installation), operating or ownership cost (operation, maintenance) and recycling or disposal costs. The LCC analysis provides important inputs in the decision-making process: product suppliers can optimize their designs by comparing competing alternatives on the same basis and by performing trade-off studies; they can also evaluate various operating, maintenance and disposal strategies and assess whether it is convenient or not to replace an old transformer. As disposal costs are relatively insensitive to the type and design of the transformer, as in the considered setting, they are seldom taken into account. EAF transformers have to operate for many years and time has an impact on the value of cash flows; consequently, future costs should be discounted in order to consider the time value of money. From the above considerations, the formulation of the life cycle cost becomes:

$$LCC = \text{Purchasing price} + \sum_{i=1}^{n} \frac{(\text{Losses cost} + \text{Cooling system cost} + \text{Maintenance cost})^{€}\!/_{year}}{(1+\rho)^{i}} \quad (1)$$

where $n$ represents the lifetime of the transformer [year], while $\rho$ is the annual discount rate [%].

Due to high specificity of EAF context, the proposed LCC approach presents relevant differences in the life cycle cost components with respect to the traditional ones.

*2.1. Purchase*

Similarly to other capital intensive equipment, the EAF transformer LCC model purchasing price is the first component included in its total cost evaluation analysis. Such a cost is determined as the result of design specifications, i.e. materials included, e.g. quantity of copper, iron and oil, dimensioning of core and windings, connections design, and so on. Moreover, different other components can be included, such as OLTC, DGA and on-line monitoring system, just to cite some. Each of them has a specific role and can be designed considering different features. For example, OLTC allows a variable number of steps to be selected, enabling voltage regulation of the output: different number of turns correspond to different costs, but also different influence on transformer performance, e.g. losses and maintenance. The sum of design choices and equipment determines the transformer purchase price.

*2.2. Energy losses*

Converting an input voltage to a different output voltage by a transformer, determines energy losses, which consist of two contributions: no-load losses and load losses. Losses in the core of a transformer are called “no-load losses” or “iron losses” because they are dependent on the magnetic core and thus they are always present when the transformer is electrified, even if the transformer is not actively supplying a load. For that reason, no-load losses are independent of the load, i.e. they do not increase with the loading on the transformer. Conversely, load losses (or “copper losses”) comprise the energy that is lost in the transformer windings and conductors due to ohmic losses as a result of the load current flowing in the windings and, thus, they vary according to the transformer loading. Another element that influences energy losses is represented by working condition of transformer. Operating conditions, i.e. real conditions, generally determines different losses from those generated under normal conditions, under which load and no-load losses are measured in the laboratory. Thus, as mentioned in the regulation CEI EN 60076-1, it is necessary to make special considerations, consisting in extra losses computation, that will increase the nominal losses of the transformer. Extra losses could be generated by different factors, such as high altitude, extreme high or low temperature, tropical humidity, seismic activity, severe contamination, unusual voltage or load current wave shapes, which cause odd and even harmonics, and intermittent loading. Considering load cycle, working conditions and related factors influencing transformer operations, losses can be computed as follows (see also [3]):

$$\text{Losses}_{cycle} = P_0 + P_k \cdot \sum_{j=1}^{m} x_j^2 \ , \quad (2)$$

$$\text{Losses cost} = \text{Losses}_{cycle} \cdot \frac{cycle}{year} \cdot \frac{€}{kWh} \ , \quad (3)$$

where $P_0$ identifies the real no-load losses, $P_k$ the real load losses, $x$ the transformer load factor (i.e. the ratio between the total actual output and the rated active power) and $m$ represents the minutes in a cycle.

Energy losses contribution to the life cycle cost represents the highest share for every transformer; however, it is still more significant for EAF transformers, as they normally operate with high load factors $x$. For that reason, it is important to compare the different alternatives not on the basis of the nominal losses; but it should be analysed the losses generated to satisfy the load cycle of interest.

*2.3. Cooling system*

Losses are represented by excess heat, which arises in the core or the windings of the transformer. In order to maintain the transformer in regular operating conditions without damaging the insulation, the cooling system has to be sized so as to dissipate the heat, i.e. to face the losses. Moreover, the temperature in oil transformer is the most important limiting factor for the loading. Consequently, a very important issue in the transformer industry is to have an efficient cooling system, that meets the required temperature rise limits, and consequently dissipates heat of core and windings. The energy to run the cooling system (i.e. cooling fans or pumps, replenishment of water losses, etc.) represents auxiliary losses in the transformer system that should be considered in the LCC model. These considerations are especially important for EAF transformer because they are usually installed near the furnace and thus the ambient temperature could reach very high temperature and also because the frequent overload and the high load factor generates higher losses. In fact, a higher ambient temperature means a higher temperature rise in the transformer (i.e. oil) so that losses can be more relevant in and EAF transformer than in a distribution one. In recent years, several cooling control systems have been introduced in order to limit those auxiliary losses: in this way, it is possible to modulate the utilization of the cooling system over the real necessity instead of the continuous use. In fact, the particular load cycle in an EAF transformer (higher variability of load during the cycle, frequent overload and high load factor than for a distribution transformer) makes the request of heat dissipation (i.e. losses) by cooling system of an EAF transformer more variable than for a distribution transformer. This situation, without the possibility to modulate the utilization of the cooling system (i.e. its energy consumption) leads to:

- an oversizing of the cooling system: the nominal power of the cooling system is determined to meet the heat dissipation requirements coming by the EAF transformer during its overload phase (worst heat condition);
- an extra energy consumption when normal (load phase) or no heat dissipation (no-load phase) is required.

Both consequences influences cooling system cost: in particular, condition (1) influences purchase cost (i.e. a larger size cooling system is more expensive than one of a smaller size), while condition (2) influences the annual utilization (energy) cost, both negatively (cost increase).

When it is possible to modulate the utilization of cooling system (i.e. it is possible to determine the power used in each cycle phase) the energy consumption of the cooling system is related to the current needs of the EAF transformer. Specifically, a certain amount of energy is required to dissipate losses during load and over-load phases, while no energy is consumed by the cooling system during no-load phase. In this case dimensioning of the cooling system is based on nominal load values. Considering this, the cooling system control, influences positively the annual utilization (energy) cost of cooling system (cost decrease), while it requires an extra purchasing cost. The decision on involving a cooling control system or not, based on costs, could be derived from the trade-off between cost components. Considering "1" the solution involving a cooling system without control, and "2" the solution involving a cooling system with control, the following relationships can be written:

$$Size_1 \leq Size_2 \,, \tag{4}$$

$$PurchaseCost_1 \leq PurchaseCost_2 \,, \tag{5}$$

$$EnergyCost_1 = Size_1 \cdot (\%Load + \%Overload + \%NoLoad) \tag{6}$$

$$EnergyCost_2 = Size_2 \cdot (\%Load + \%Overload) \tag{7}$$

$$\Delta = PuchaseCost_1 - PuchaseCost_2 + EnergyCost_1 - EnergyCost_2 \tag{8}$$

If purchase cost of cooling system control (usually with a limited increase in the purchase price of cooling system) is smaller than the value of $\Delta$, it is convenient to purchase the control unit for the cooling system. On the other hand, cooling control can be dimensioned on the basis of worst heat dissipation requirements (overload phase). In this case, the cooling system with control component assumes the same size as without control component, so no purchase cost decrease are involved. However, the oversized cooling system can better face temperature rising during the overload phases, thus improving the EAF transformer performance in terms of losses reduction. In this case, an oversized cooling system (with or without control component) leads to a higher purchase cost, but an annual energy (losses) cost decrease. As usual, the economic trade-off between purchase price of cooling system and energy cost due to losses should be evaluated to define the optimal size of the cooling system, considering also the introduction of a control unit to modulate its utilization. Finally, cooling system configuration can influence also maintenance aspects. In fact, when choosing the size of the system, a different number of units can be involved: the plurality of units can increase the reliability of the cooling system: in case of a failure of one unit, the others can work, leading to a continuous, even if in a degrade manner, dissipation of losses.

### *2.4. Maintenance*

The annual cost of maintenance consists of three main contributions:

- the annual cost of maintenance activities: cost for inspections and actions performed every year or in case of a degrading condition to maintain the transformer (e.g. the oil analysis);
- the out of service cost, i.e. the steel production lost due to downtime;
- the reliability penalty of the transformer, i.e. the multiplication between the cost and the probability of failure, where probability of failure is function of the age of the transformer and of the maintenance activity performed.

The first two categories of maintenance costs, i.e. intervention (annual or periodic) and out-of-service costs, are strictly related to the physical performing of a maintenance activity, and usually they are the only perceived maintenance cost. Typical maintenance activities may involve:

- ordinary maintenance, i.e. a general check of all components of the EAF transformer, that influences the overall transformer condition;
- oil inspection and correction, that restores oil conditions;
- active parts inspection, used to verify and in part restore active parts conditions;
- OLTC replacement, which is a function of number of cycles and number of taps per each cycle.

Each activity is characterized by a cost (annual or periodic) and a degree of influence on the failure probability of the EAF transformer (or at least on a component, e.g. oil, active parts, OLTC): both these elements determine what is called the *reliability penalty*. Excluding a certain action from the list of maintenance activities can keep maintenance cost at a low value, but failure probability can assume high values (i.e. short lifecycle of the EAF transformer), and the value of reliability penalty is used to quantify the effect of such exclusion. By performing maintenance actions, related cost may arise, but failure probability assumes lower values and a longer EAF transformer lifecycle can be reached: once again reliability penalty value defines the effect of performing a certain maintenance activity. The difference value between reliability penalty values performing or not performing a certain maintenance activity gives quantitative effects on costs (and lifecycle, considering the failure probability) of the EAF transformer. Moreover, failure probability of an EAF transformer (in terms of longer lifecycle of the transformer) can also be positively influenced by the presence of an online DGA device, and an online monitoring system: these devices can help to predict degrade conditions and to prevent it, decreasing probability of future failures. In particular, DGA and online monitoring system involve purchase costs that are about 5% of EAF transformer purchase price. Considering maintenance costs, intervention and out-of-service may cover the 99% overall annual maintenance cost (about 10% of annual cost due to losses), so that reliability penalty does not show a great effect from the economic point of view, but the EAF transformer lifecycle extension, deriving from performing appropriate maintenance activities, can reduce the need of components and even transformer replacement.

## 3. Numerical study

In the present section, a numerical example is proposed comparing two different EAF transformers, considering the same load cycle: 45 min at 160 MVA and 15 min at 0 MVA (off). The EAF for the steel casting operates continuously for 250 days a year and the LCC of the transformers has been performed considering a lifespan of 20 years. Firstly, we consider a 140 MVA transformer with a 15% overload (Solution A) and then a 160 MVA transformer (Solution B), both of them with an OFWF (i.e. Oil Forced Water Forced) cooling system sized 2x75% (i.e. 2 cooling units, each facing 75% of required losses dissipation potential). Other parameters necessary to perform the LCC analysis are: the annual discount rate (ρ = 5%), the electricity cost (0.15 €/kWh) and the price of the steel production (100 €/ton). In the specific example, we consider the following purchasing prices, rated no-load losses and load losses and cooling system cost (Table 1).

Table 1. Purchasing price, no-load and load losses and cooling system cost for a 140 MVA and a 160 MVA transformers.

| | | Solution A | Solution B |
|---|---|---|---|
| Rated power | [MVA] | 140 | 160 |
| Purchasing price | [k€] | 1200 | 1500 |
| No-load losses | [kW] | 62 | 60 |
| Load losses | [kW] | 800 | 800 |
| Cooling system cost | [k€] | 29.54 | 21.02 |

The auxiliary losses generated by the OFWF cooling system are expressed as a function of the cooler power, and they correspond to the energy necessary to run the oil and the water pumps, the energy to maintain the ambient temperature at acceptable values and the energy required to replenish the water evaporated. As can be seen from Table 1, even though the EAF transformers are served by the same type of cooling system and are characterized by almost the same rated losses, the cooling power required to dissipate the heat is different for the two solutions, as the effective losses generated during the load cycle are different. In particular, the transformer with lower rated power presents a higher load factor and thus losses are larger. Moreover, for both transformers, the user incurs in about 50 k€/year and 100 hours of out-of-service for the inspections and the maintenance activities, while the failure probability follows the trend reported in Fig. 1.

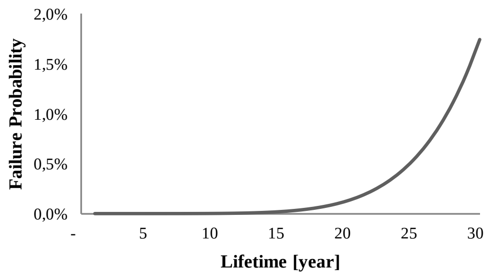



Fig. 1 – Failure probability of the EAF transformer

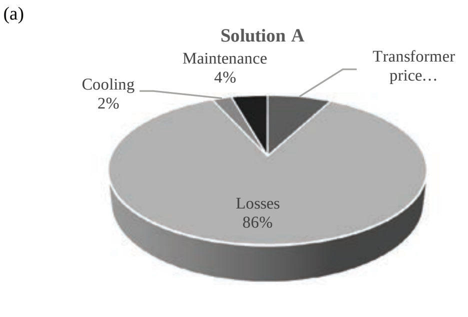
The results of the LCC analysis performed (Table 2 and Fig. 2) show that losses costs are much more relevant than the other components for both solutions, reaching about the 80% of the entire lifecycle cost. In addition, it is also possible to observe that cooling system and maintenance costs are not negligible, as they are comparable with the investment price, so they should be considered when purchasing a new transformer. Moreover, from the comparison between the two alternative solutions it is possible to observe that solution A presents a lower purchasing price than solution B, but higher cost due to energy losses, while cooling system and maintenance cost components are comparable. As an overall result, when considering the EAF transformer in its real operations, solution B is characterized by a lower lifecycle cost. Moreover, it is also interesting to compare two alternatives which differ for the cooling system: in Table 2 both the solutions are with a fixed cooling power which cannot be modulated on the real needs; while in Table 3, the only change introduced in the design is the installation of a cooling control system.

Table 2. LCC results for the alternative EAF transformers without cooling control system.

| | | Solution A | Solution B |
|---|---|---|---|
| Life cycle cost | [k€] | 15,541 | 12,806 |
| Transformer price | [k€] | 1200 | 1500 |
| Losses cost | [k€] | 13,296 | 10,364 |
| Cooling system cost | [k€] | 368.12 | 261.97 |
| Maintenance cost | [k€] | 677.15 | 679.76 |

Table 3. LCC results for the alternative EAF transformers with cooling control system.

| | | Solution A | Solution B |
|---|---|---|---|
| Life cycle cost | [k€] | 15,490 | 12,778 |
| Transformer price | [k€] | 1230 | 1530 |
| Losses cost | [k€] | 13,296 | 10,364 |
| Cooling system cost | [k€] | 286.67 | 204.24 |
| Maintenance cost | [k€] | 677.15 | 679.76 |



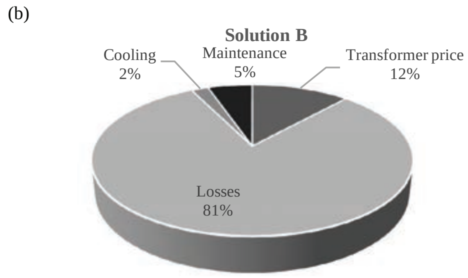




Fig. 2 (a), (b). Life-cycle cost components for the two EAF transformer alternatives without cooling control system.

From Table 3, it is evident that, with an increase of 2.5% - solution A (2% - solution B) in the purchasing price, it is possible to obtain a reduction of 22.13% (22.04%) in the cooling system cost and of 0.33% (0.22%) in the life cycle cost. As expected, in the solution characterized by higher overloading and thus in the presence of an oversized power cooling, the cooling control has higher effects in the auxiliary losses.

Since the lifetime of EAF transformer is quite long, the discount rate is a relevant parameter. Fig. 3 shows how the incidence of the different cost components changes with different discount rates: for higher values the impact of purchasing price is higher and thus the two solutions reach closer lifecycle costs. Realistic values for the discount rate are around 3-5%, from the following figure it is possible to observe how for that values the difference between the two solutions is very significant.

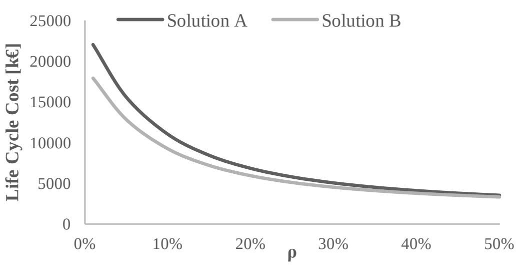



Fig. 3. Influence of the discount rate on the lifecycle cost of the EAF transformers.

## 4. Conclusions

The improvements performed in the last decades on the EAF do not reach the limit in terms of process efficiency optimization and impact of steel manufacturing on the worldwide total energy consumption minimization. Consequently, further developments are still request. However, going on with investment in the furnace's performance would only cause high costs with few benefits. The main opportunity is, thus, to adopt a holistic approach taking into account all the relevant components of the process system, especially the electric transformer, since greater part of the melting energy pass through it. In literature, LCC analyses on the transformer already exist but none of them are specific on the EAF transformer. As EAF transformers are exposed to specific and more critical conditions than power and distribution transformers, it becomes crucial to consider real operations conditions when carrying out performance analyses on such transformers. The aim of the present work, in collaboration with TES Transformer Electro Service Srl., is to extend the LCC approach to this specific context, developing a model to determine total ownership cost of EAF transformers, including purchase, losses, cooling system and maintenance cost components during the entire lifecycle of the transformer. The main strengths of the presented model, produced by this joint collaboration, are: the evaluation of a technological solution that best suits the system requirements to minimize electrical losses, by incorporating in the overall costs assessment for operating and maintaining the system components (i.e. on-load-tap changer, coolers and oil pumps); the integration of savings on the costs associated with the operation, flow and efficiency of the cooling system components, such as pumps, thus preventing the machine from being subjected to useless and hazardous temperature changes by using feedback regulation systems incorporated in the process control system; finally, the implementation of a monitoring and control system for the transformer and its main components to improve their lifecycle and planned maintenance interventions according to a schedule determined on the basis of actual utilization. A numerical example has been proposed in order to show the impact that real conditions and operation and maintenance costs have on the purchasing decision, by comparing two alternative design solutions.

## References

[1] Worldsteel Association, 2012. Sustainable Steel: At the core of the green economy, Worldsteel, p. 11.

[2] Samet, H., Ghanbari, T., Ghaisari, J., 2014. Maximizing the transferred power to electric arc furnace for having maximum production. Energy, vol. 72, p. 752-759.

[3] De Watcher, B., 2013. Application Note: Transformer replacement decisions. Leonardo Energy: Cu0185.

[4] Waide, P., Scholand, M., 2014. PROPHET II: The potential for global energy savings from high-efficiency distribution transformers. Waide Strategic Efficiency Limited and N14 Energy Limited.

[5] Stopar, K., Kovačič, M., Kitak, P., Pihler, J., 2014. Electric-arc-furnace productivity optimization. Materials and Technology, vol. 48 (1), p. 3-7.

[6] Jeromin, I., Balzer, G., Backes, J., Huber, R., 2009. Life Cycle Cost Analysis of transmission and distribution systems. IEEE Bucharest Power Tech Conference, June 28th – July 2nd, Bucarest, Romania.

[7] IEC 60300-3-3 "Dependability management Part 3-3: Application guide – Life cycle costing". International Standard.