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Product-Service Systems across Life Cycle

Product-service system for sustainable EAF transformers: real operation conditions and maintenance impacts on the life-cycle cost

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Abstract

Steel industry is one of the largest energy consumers in the manufacturing sector and covers a great share of the total energy consumptions in the world. As in recent years, energy efficiency has been a top priority for the European Commission, which set a reduction of 20% as a target for the energy consumption, so that great improvements in energy performances are required. Many improvements have already been introduced in the Electric Arc Furnace (EAF) process and additional progresses are very difficult to be achieved. Consequently, the main opportunity consists in the improvement of other system components, especially of the transformer's performance, as it is an expensive component with a strategic relevance for EAF operation. A more energy-efficient transformer can make a valuable contribution to European energy savings: lower energy losses substantially correspond to lower running costs. However, recent EAF transformers from different firms have become equally well performing, thus, the basis of the competition has been shifted from the single product offered to a customized solution that should fulfill specific customer needs. In other words, in order to obtain an advantage on the main competitors, some additional services, that are needed during the use phase of the product, are added. These extra services take into account the real energy losses obtained during the operation of the EAF and the maintenance activities. To perform the economical analysis of the solution, it is thus necessary to calculate the EAF transformer's life cycle cost (LCC) or total cost of ownership (TCO), over the life span of transformer. At the present, no works have been conducted on the EAF transformer which are exposed to more critical conditions than power/distribution transformers, and no real conditions have been considered even for other forms of transformer. In addition, the only aspects that have been taken into account in the existing transformer's LCC were the purchasing price and a share of the total relevant costs of losses (no-load and load losses). Thus, the aim of the present work consists in the evaluation of a solution consisting of a tangible product (EAF transformer) and intangible services (e.g. maintenance activities, operational consultancy) that best satisfy the EAF operations' requirements, in order to simultaneously enhance competitiveness and support sustainability. Moreover, the other relevant contribution is the integration of maintenance aspects and failure risk, as design decisions affect also transformer's reliability and related maintenance activities.

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Keywords: EAF transformer; life-cycle cost; maintenance; product-service system.

1. Introduction

In recent years, energy efficiency has been a top priority for the European Commission, which set a reduction of 20% as a target for the energy consumption. Among the manufacturing sector, which is the greatest world energy consumer [1], energy efficiency represents a relevant opportunity especially in the steel industry, since it is characterized by a very energy-intensive production process consuming a huge amount of resources such as electrical and chemical energy (e.g. oxygen,

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natural gas, oil, carbon) [2]. In the past decades, in order to improve energy performance and quality of the steel-making process, huge improvements for the Electric Arc Furnace (EAF) have been introduced, which aims were: stability of the arc maximization, electric disturbances on the power supply network (flicker) reduction, productivity increase, electrode consumption reduction and cost of EAF's equipment and operation optimization [3]. Some examples of these improvements are: 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 in series. In spite of these several improvements, energy still represents a significant share of the total cost of steel production; thus, further developments in the process energy efficiency are needed in order to reach higher competitiveness and greater savings. However, additional progresses in the furnace are now difficult to be achieved, since the easier measures have already been performed. Consequently, the main opportunity to improve the global efficiency of the process consists in the improvement of relevant system components, especially focusing on the electric transformer, which is of a strategic relevance for EAF operations because greater part of the melting energy passes through it. A more energy-efficient transformer can make a valuable contribution to European energy savings and can lower process's energy losses, considerably reducing the running costs. For that reason, recently, EAF transformers of different firms have become equally well performing, reaching consistent reductions of the rated load and no-load losses. As a consequence, the basis of the competition has been shifted from the single product to a customized solution, consisting of 'tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs in an economical and sustainable manner', which in literature has been discuss under the topic of product-service system (PSS) [4]. Intangible value is currently the key to obtain competitive advantages and to overcome the competitors' performances. Moreover, this intangible added value makes the client willing to pay more than would be justified on the basis of rationality. Recent contributions ([4,5]) underline how PSS business models are emerging phenomenon, as they allow firms to create new sources of added value and competitiveness, satisfying client needs in an integrated and customized way and allowing clients to concentrate on core activities. Through PSS business model it is also possible to build unique relationships with clients, to enhance customer loyalty and to innovate faster since the firm knows better the needs of the market and the problems to face. The EAF transformer solution can be defined as a product-oriented service, according to the widely accepted classification in [4]: the provider (i.e. EAF transformer producer) sells a product, but also offers extra-services that are needed during the use phase, e.g. maintenance activities, and gives advice on the most efficient use of the transformer, taking into account the real energy losses obtained during the operation of the furnace and the auxiliary equipment (e.g. cooling system). The solution proposed aims to improve the economic and environmental efficiency of the process, reducing the life-cycle cost and increasing the sustainability of the EAF transformer: incremental efficiency improvements (e.g. through maintenance contract in a product-related service) can lead to a prolonged life and/or less use of energy and auxiliary materials. To perform the economic analysis of the solution, it is thus necessary to calculate the EAF transformer's life cycle cost (LCC) or total cost of ownership (TCO), over its lifespan, taking into account the purchasing price, the costs of energy losses (no-load, load, LV terminals and auxiliary losses) and the cost due to maintenance's activities. At the present, no works have been conducted on the specific context of the furnace process and thus on EAF transformers, which are exposed to more critical conditions than power/distribution transformers, and no real conditions have been yet considered even for other forms of transformer. In addition, the only aspects that are usually taken into account in the transformer's LCC are the purchasing price and a share of the total relevant costs of losses (no-load and load losses) [6,7].

The present work has been developed in collaboration with TES Transformer Electro Service Srl, an important Italian reality in high-power and special transformers market, whose commitment is precisely to offer tailor-made EAF transformers with extra services valuable for the users. The aim of the collaboration consists in the evaluation of the solution, involving of a tangible product (EAF transformer) and intangible services (e.g. maintenance activities, operational consultancy), that best satisfy the EAF operation requirements, in order to simultaneously enhance competitiveness and support sustainability. Moreover, another relevant contribution is the integration of maintenance aspects and failure risk into the definition of the solution, as design decisions affect also transformer's reliability and related maintenance activities.

2. EAF Transformer operation

The EAF transformers' operation is controlled by the melting process and thus by the furnace, consequently this special type of transformer is subject to more critical conditions compared with power and distribution transformers [8]: i.e. very high secondary currents, low secondary voltage, heavy current fluctuations, unbalanced conditions, switching transients, harmonics, short circuits, mechanical stress, frequent overloading conditions, vibrations, high ambient temperature, pollution and dust. These severe conditions worsen the performances and lower the lifetime of the EAF transformer. Thus, a higher focus on additional services, that control maintenance activities and guarantee the correct utilization of the transformer, leads to better performance of the product during its lifetime.

In order to achieve customer satisfaction, the challenge for suppliers is to design solutions that are reliable, cost competitive and that meet operation requirements: such a goal can be reached by optimizing acquisition, ownership and disposal costs. The ownership phase acquires great relevance especially in the EAF transformer lifetime cost and reliability: in fact, higher energy losses (in the form of heat) cause higher costs and higher degrade of the insulation over time. Moreover, a transformer with high efficiency reduces the amount of cooling power generation needed to accommodate the losses (both core and coil) and thus lower auxiliary energy losses. Further, reduced losses implies an improvement in the failure rate, which corresponds to a higher reliability level that contributes to reduce possible production losses that could occur. So, the focus on the efficiency and reliability of the system means a longer lifetime and reduced system degradation. In other words, since the transformer design affects all relevant performance, i.e. safety, reliability, maintainability, maintenance support requirements, etc., the solution offered by the provider should be influenced not only by the acquisition price but also by the expected ownership cost, i.e. mainly energy losses cost and maintenance cost:

$$LCC = Price + \sum_{i=1}^{n} \frac{Energy\ losses\ cost + Maintenance\ cost}{(1+\rho)^{i}} \quad (1)$$

where n represents the lifespan of the EAF transformer [year] while ρ the annual discount rate [%]

The proposed LCC analysis provides important inputs in the decision-making process, leading to a better economic and sustainable evaluation: product suppliers can optimize their designs by comparing competing alternatives on the same basis and by performing trade-off studies; they can evaluate various operating and maintenance strategies and assess whether it is convenient to replace an old transformer or it is better to revamp the existing one. Disposal costs are mainly due to the operations for dismantling and disassembling the EAF transformer, recovering materials and processing wastes: such operations are not differential for the power range of transformers considered in the analyses since the operations depend on the sizes of the transformers and these sizes are similar; consequently disposal costs are not taken into account.

2.1. EAF Transformer's price

EAF transformers are capital intensive equipment, thus, the first component to be included in the LCC model is represented by purchasing price. This cost is mainly the result of design specifications, i.e. materials included (copper, iron and oil quantities), dimensioning of core and windings, LV and HV terminations, etc. Some additional components, with specific roles and alternative design and features, can be included in the transformer in order to improve the global performance: such as the on load tap changer (OLTC), the dissolved gas analysis (DGA) and the on-line monitoring. The OLTC, e.g., allows the selection of a variable number of steps, enabling voltage regulation of the output: different number of turns correspond to different costs and also different influence on transformer's losses and maintenance. Design choices and additional equipment determines the final transformer purchase price.

2.2. Energy losses

The main task of any EAF transformer is to convert the electrical, voltage and current parameters required to melt ferrous metals using electric arc technology. This conversion process, however, determines relevant energy losses at every operation cycle (P_{cycle}) which mainly consist of three contributions: power losses in industrial transformers can be no-load losses, P_0 (i.e. dependent on the magnetic core), load losses, P_k (due to ohmic losses in the windings and conductors) or additional losses, P_a (i.e. dependent on the geometry of the machine and design engineering, e.g. the LV terminals, on the type of load and on auxiliary equipment as the cooling system).

$$P_{cycle} = P_0 + (P_k + P_a) \sum_{j=1}^{m} x_j^2 t_j \quad (2)$$

where x represents the transformer load factor (i.e. the ratio between the total actual output and the rated active power), m the number of load factor combinations and t_j the time characterized by each load factor combinations [h/cycle].

In order to evaluate the annual cost allocated to the energy losses, the value of P_{cycle} obtained from eq. (2) should be multiplied by the electricity cost and by the number of production cycle per year.

Electrical losses in EAF transformers present two problems: one of a technical nature – they produce heat that increases operating temperature, which needs to be dissipated using costly cooling system – the other of a purely economic nature – energy losses cost money as does the decrease in efficiency during the cooling process [9]. In order to reduce those energy losses, some opportunities exist. Firstly, a tailor-made EAF transformer produced to satisfy specific requests, responding to the actual load cycle of the system in which it will be installed, and then the integration of smart solutions in the product (e.g. smart cooling and maintenance systems). Every transformer should be chosen given the specific load cycle it has to satisfy as it is a component of a system and does not operate individually. Thus, the tailor-made solution acquires great relevance. In addition, as losses are represented by excess heat, 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. As a consequence, a very important issue in the transformer industry is to have an efficient cooling system. The energy to run the cooling system (i.e. cooling fans or pumps, replenishment of water losses, etc.), which is a function of the cooler power, 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 overloaded (i.e. higher load factor) and installed near the furnace and, thus, the ambient temperature could reach very high temperatures, which means higher temperature rise in the transformer, with consequent higher losses than in a distribution transformer. In recent years, smart cooling control systems have been introduced to limit those auxiliary losses: in fact, they allow to modulate the utilization of the cooling system over the actual request of heat dissipation necessary for the specific load cycle, instead of the continuous use. Thus, with a limited increase of the purchasing price, it is possible to have lower auxiliary losses trough the lifespan of the transformer.

A similar innovative product has been developed by TES Transformer Electro Service Srl, in which it is possible to calibrate the energy supply on the basis of the actual use of the system (i.e. energy is consumed only when needed, depending on the actual environmental conditions and production flows). In addition, it has been equipped with a smart cooling and maintenance system that guarantees control interventions over time and greater reliability.

2.3. Maintenance

The maintenance of an industrial transformer has a high contribution to the lifetime of the equipment, as well as to its reliability and availability. Maintenance policies depend on many factors such as importance of the unit, costs of outages, costs of maintenance interventions, etc. For that reason, the inclusion of such issues in extra services offered by the provider, which has a higher knowledge on the product than the final user, can improve the global performance of the unit during its lifetime. The annual cost of maintenance M consists of the annual cost of ordinary maintenance activities, M_a (i.e. the cost for annual or periodic 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, M_o (i.e. the steel production lost due to downtime) and the reliability penalty of the transformer, M_p (i.e. the product between the probability of failure and the transformer purchasing price). The probability of failure, f, is a function of the age of the transformer and of the maintenance activity performed [6]. Such a function is determined case-by-case; an example is presented in Fig.1, developed with TES data.

$$M = M_a + M_o + M_p \tag{3}$$

$$M_o = s \cdot Q_{lost} \tag{4}$$

$$M_p = \sum_{i=1}^{n} f_i \cdot Price \tag{5}$$

$$Q_{lost} = \frac{t_o \sum_{j=1}^{m} x_j t_j W_j}{\sum_{j=1}^{m} t_j \, SEC} \tag{6}$$

$$W_j = P_{nom} \cdot cos\varphi_j \tag{7}$$

$$f_i = \alpha i^{\beta}[(1 - w_{ins}y_{ins})(1 - w_{DGA}y_{DGA})(1 - w_{online}y_{online})] \tag{8}$$

where s is the steel's value [€/ton], Q_{lost} the quantity of steel's production lost in the downtime, t_o the out-of-service time [h/year], W_j the rated power of the transformer for the load factor combination j [kW], P_{nom} the nominal power [MVA], $cos\varphi_j$ the power factor for the specific load factor j, SEC the specific energy consumption for the production process [kWh/ton], α and β the parameters of the Weibull distribution describing the failure rate function, w the failure rate after the considered maintenance events (i.e. active parts inspection, DGA, online monitoring) and y binary variables which assumes the value 1 if the events are undertaken and 0 otherwise.

If the maintenance policy is not correctly developed, the last two contributions of the total maintenance cost represent a significant share of the total life-cycle cost. The specific maintenance interventions that can be configured in the model, characterized by a cost (annual or periodic) and a degree of influence on the failure probability of the EAF transformer, are: active parts inspections, OLTC maintenance and/or replacement, oil correction, ordinary maintenance, DGA on-line and on-line monitoring of other relevant parameters for the EAF transformer. In recent years, an increasing array of devices for on-line monitoring and data logging of various transformer parameters have acquired relevance. Thus, the presented LCC analysis has been modelled also to evaluate the cost-benefit of such on-line monitoring systems, comparing the ability of such systems to reduce transformer failure rates against their purchasing price. In order to evaluate the economic aspects of on-line monitoring it has been considered the probability of failure both with and without on-line monitoring, as it is recommended in [10]. Moreover, in order to adequately estimate the probability of failures, it is also presented how it can be easy to construct a failure probability tree.

3. Numerical examples

In order to observe the benefits introduced with the PSS approach, two examples have been proposed. Firstly, it has been considered a scenario in which the purchase of a new EAF transformer is needed and, then, the scenario in which a revamp is sufficient. In both the examples, it has been compared the life-cycle cost of two alternative solutions given a specific load cycle ($m = 3$): 15 min at 120 MW, 35 min at 140 MW and 10 min at 0 MW (off). The EAF for the steel casting operates continuously for 250 days a year, executing 24 cycle a day, and the SEC for the production process is 400 kWh/ton. The LCC of the transformers has been performed considering a lifespan of 20 years.

3.1. Example 1: EAF transformer replacement

Firstly, we consider a 120 MVA EAF transformer with a consequent 17% overload for solution A, and a 140 MVA transformer for solution B. The power factors considered for the computation of rated powers for different load factors are reported in Table 1:

Table 1. Power factors

$Cos\phi_j$	Solution A	Solution B
j=1 (120 MW)	0.999	0.997
j=2 (140 MW)	0.999	0.999
j=3 (0 MW)	0.983	0.983

Both solutions involve 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). Solution A consists of a smaller transformer with lower rated energy losses and purchasing price. With solution B the provider aims to satisfy better the real needs of the furnace operation (i.e. tailor-made solution with smart cooling system) and, thus, a transformer with higher rated power and extra services (i.e. on-line maintenance interventions, active parts inspection, etc.) is proposed, even though the user will incur in higher purchasing price. In Table 2 are shown the specific variables for the evaluation of the failure rate in both the scenarios:

Table 2. Failure rate's variables

	Solution A	Solution B
w_{ins}	70%	70%
w_{DGA}	20%	20%
w_{online}	15%	15%
y_{ins}	1	1
y_{DGA}	0	1
y_{online}	0	1

Other parameters necessary to perform the LCC analysis are: the Weibull's parameters ($\alpha = 5E - 10, \beta = 6.5$), the out-of-service time (68 h), the annual discount rate (ρ = 5%), the electricity cost (0.15 €/kWh) and the value of the steel production (100 €/ton). Table 3 shows the nominal powers, purchasing prices, rated no-load and load losses, additional losses and maintenance activities cost considered in the analyses.

Table 3. Purchasing price, no-load and load losses for a 120 MVA and a 140 MVA transformers.

		Solution A	Solution B
Nominal power	[MVA]	120	140
Purchasing price	[k€]	1000	1300
No-load losses	[kW]	65	70
Load losses	[kW]	575	650
Additional losses	[kW]	261.4	292.2
Maintenance activities	[k€/year]	51	54

The furnace load cycle determines a higher load factor for the EAF transformer with lower rated power (solution A) generating higher energy losses, mainly due to higher load and auxiliary losses: e.g. 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 solution B, extra services improving the maintenance interventions are included: Fig. 1 shows the early failure rate of the two solutions.

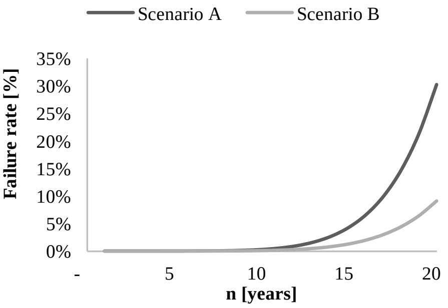

Fig. 1. Early failure rate for the two EAF transformer alternatives.

In Table 4, the results of the LCC analysis are shown. The main statements that can be carried out are that losses costs are much more relevant than the other components for both solutions, reaching more than the 75% of the entire lifecycle cost; the load cycle of the specific furnace operation is too relevant in the analysis of the real energy losses and thus tailor-made solution leads to lower costs over the lifespan; finally, extra services offered from the provider in order to reach higher levels of maintenance implies higher purchasing price and maintenance cost, but also higher life expectancy and performance leading to a better global LCC. From Table 4, it is evident that, with an increase of 30% in the purchasing price and of 6% in the maintenance initiatives costs (from solution A to solution B), it is possible to obtain a reduction of 11% in the life cycle cost, due to the higher efficiency of the system operations, i.e. to the lower real energy losses and lower early failure rate.

Table 4. LCC results for the alternative EAF transformers.

		Solution A	Solution B
Life cycle cost	[k€]	13,256	11,725
Transformer price	[k€]	1,000 (7.5%)	1,300 (11.1%)
Losses cost	[k€]	10,523 (79.4%)	8,890 (75.8%)
Maintenance cost	[k€]	1,733 (13.1%)	1,535 (13.1%)

3.2. Example 2: EAF transformer revamping

In order to maximize the steel production of the furnace, EAF transformers are usually forced to operate in frequent and severe high overloading conditions, worsening the performance of the EAF transformer and shortening its life expectancy. For that reason, the purchasing of new tailor-made transformers leads to great LCC reduction and to lower failure probability. However, since the capital requested for the change of the EAF transformer is not negligible, sometimes it is necessary to consider a revamping of the existing equipment instead of its replacement. The subsequent installation, related to an existing EAF transformer, of smart equipment for the cooling system and for maintenance interventions (such as cooling control system, DGA on-line control, on-line monitoring, etc.) leads to savings that are not negligible, so that the revamping of the existing transformer represents a valid alternative. In example 2, solution A is compared to a similar solution involving the same transformer, but with the additional extra services and smart equipment, previously defined, in order to improve the performance of the global system (solution C). In the present example, the investment cost that increases the transformer price for solution A is null as no changes are introduced with respect to the as-is scenario; while, for solution C it is constituted by the purchasing price of the different additional equipment introduced.

Table 5. LCC results for the alternative solution given an existing EAF transformers.

		Solution A	Solution C
Life cycle cost	[k€]	12,256	11,809
Additional transformer price	[k€]	-	100
Losses cost	[k€]	10,523	10,523
Maintenance cost	[k€]	1,733	1,186

Table 5 shows the results of the EAF transformer revamping: it is possible to observe that the installation of the smart equipment and the definition of a maintenance policy that best fits the real operation leads to cost savings over the lifespan; even though these savings are lower than the one introduced with the replacement of the transformer (less than 1% in total life cycle cost). As a consequence, the revamping constitutes a valid opportunity to the replacement in case of few capital availabilities.

4. Conclusions

Steel industry is one of the largest energy consumers in the manufacturing sector, even though many improvements in the energy efficiency have already been introduced in the Electric Arc Furnace (EAF) process. Consequently, further developments in the energy performance are still requested. However, additional technical and technological progresses are now uneconomical, i.e. high costs for few benefits. The main opportunity consists, thus, in the improvement of the EAF transformer's performance, as its relevance due to the fact that all the melting energy passes trough it. Recent EAF transformers have become indistinctly well performing in terms of rated performances. As a consequence, the basis of the competition has been shifted from the single product to a customized solution, consisting of tangible products and intangible services designed and combined to fulfill specific customer needs in an economical and sustainable manner (PSS). The intangible value is currently the key to obtain competitive advantages and to overcome the competitors' performances. These extra services take into account the real energy losses obtained during the operation of the furnace in order to design a tailor-made transformer, the provider consultancy on the efficient operation of the product and the integration of maintenance initiatives. To perform the economical analysis of the solution, it is thus necessary to calculate the EAF transformer's life cycle cost (LCC) taking into account the purchasing price, the costs of energy losses (no load, load, LV terminals and auxiliary losses) and the cost due to maintenance. At the present, no works have been conducted on the EAF transformers, which are exposed to more critical conditions than power/distribution transformers. The aim of the present work, performed in collaboration with TES Transformer Electro Service Srl, consists in the evaluation of the solution involving of a tangible product (EAF transformer) and intangible services (e.g. maintenance activities, operational consultancy) that best satisfy the EAF operations' requirements, in order to enhance competitiveness and to support sustainability simultaneously. Moreover, the other relevant contribution is the integration of maintenance aspects and failure risk, as design decisions affect also transformer's reliability and related maintenance activities. Two numerical examples have been proposed: first, two alternative solutions have been compared when the replacement of the EAF transformer is needed and, as a second case, it has been analysed the impact of revamping the already installed transformer. With both the examples, it is possible to observe the great relevance that the extra services have on the LCC of the system and, thus, on the competitive advantages of the provider.

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