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Magnetic field-based arc stability sensor for electric arc furnaces

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ABSTRACT

During the last decades the strategy to define the optimal Electric Arc Furnaces (EAF) electrical operational parameters has been constantly evolving. Foaming slag practice is currently used to allow high power factors that ensures higher energy efficiency. However, this performance depends on strict electric arc stability control. Control strategies for these are normally defined for alternating current furnaces (AC EAF) and are based on intrusive and highly expensive systems.

In this work we analyze the variation of the magnetic field vector around the direct current EAF (DC EAF) and its relationship with arc stability. We propose a cheap stability control system with no installation or integration requirements and thus, easily implementable to both AC and DC EAFs. To this end we have built a non-intrusive and low-cost 3-axis Hall-effect sensor that can be mounted neighboring the furnace's electrical bars. The sensor allows acquiring the magnetic field magnitude and orientation that provides a newly defined arc stability factor metric. This proposed Arc Stability Index has been compared with three different alternative well established and more expensive measurement methodologies obtaining with similar results. The proposed index serves as a closed loop signal to the electrical regulation for controlling the arc voltage, ensuring the most convenient arc length that guaranties non-instabilities. The new system was developed and industrially validated at two different DC EAF's in ArcelorMittal demonstrating an improvement of 6.7 kWh per Liquid steel ton during the evaluated period and a time reduction of 1.1 min per heat over the current standard procedure. Additional validation tests were also carried out also in ArcelorMittal AC EAF proving the capability of this technology for both AC and DC of furnaces.

1. Introduction

In modern steel production, steel can be obtained by two different processes: Iron-making route (from iron ore) and electrical steelmaking route (from scrap metal). Both processes follow two subsequent stages of oxidizing and reducing the steel to adequate the component to the steel grade requirements. In both cases, the main objective of metallurgic processes is to produce a product that complies with the final products specifications. These requirements highly depend on the final composition of the steel. Other metallurgic processes also make use of oxidizing-reducing subsequent stages to obtain materials with the appropriate quality requirements such as silicon manufacturing [1,2].

Focusing only in steelmaking, and given the flexibility required nowadays to quickly adapt the production volumes according steel market demand variations, electric steelmaking process presents some important advantages over iron making route such as flexibility, higher productivity and higher process yield. However, one of the main drawbacks is the low energy efficiency of the process, since approximately 40% of the total energy consumed by the EAF represents energy losses [3].The usual energy balance for EAF proves that there is significant room for improvement when balancing productivity requirements with efficient energy input strategies [4]. The awareness by steelmaker on this concept has motivated continuous development of new process monitoring [5–7], control [8,9] and optimization methods [10–12] aiming to reduce production costs, while maintaining targeted steel quality (steel grade), facility productivity and meeting environmental standards (carbon emissions).

The electrical energy input factor has been thoroughly analyzed as the most determinant for the optimal EAF electrical operational control. Control strategy has evolved considerably [17]. In the 1970's increased powering emphasized the minimization of

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refractory erosion and, consequently, low levels of voltage, reactance and power factor were recommended. After the arrival of the water-cooled panels it was possible to operate with higher voltages during a great period of the melting period and a significant reduction in electrode consumption was achieved. Later, in the 1980̂s, the development of the foamy slag [18] allows a new voltage increase, also during the flat bath period, leading to further power increment and electrode consumption reduction. Presently, it was confirmed that good foamy slags allow the operation with very high-power factors at the last stage of melting, without arc instability [21].

Fig. 1 depicts the influence of foaming performance of slag on the energy input efficiency. However, it is not always possible to control the chemical aspects of the process, and it is often necessary to act over the electrical parameters to ensure that the process is stable. Currently there are several methodologies to estimate the appropriate level of voltage that yields to a minimization of arc instabilities while maintaining an optimal productivity. As over 85% of electric steel is made in AC EAFs and only 15% is made in DC EAF [16], most of the efforts to increase the arc efficiency have been conducted on AC technologies. The most extended method consists of analyzing harmonics generated in the electrical supply by the arcs as a foaming slag monitor by mean of Rogowski coils [19]. These approaches had been normally used to predict and correct the effect of the power network disturbances caused by AC EAF operations [13–15,20,21] and for arc instability estimation [22] and have been successfully built and fitted to the electrode power cables [23], as a better foaming slag leads to a more stable arc and fewer harmonics. However, they cannot be used for DC EAF measurement. Other methodologies include the analysis of high-frequency acoustic signal processing [24] or measurement of the Optical Emission produced by the electrode arcing [25] but these control methodologies require technical installation in EAF and, so that can be consider as intrusive methods.

On the other hand, it is common knowledge that the strong magnetic fields on EAF proximities present high variation during arc instabilities and its online measurement can be considered a good indirect measurement of the arc stability. Although there are numerous approaches for magnetic field measurements [27]. Hall effect-based sensors have proven successful for metrology [26] fault detection on power systems [28], broken rotor bars diagnosis in large induction machines [29] and numerous applications for non-destructive essays [30] even for highly sensitive scientific applications with a very low cost [31].

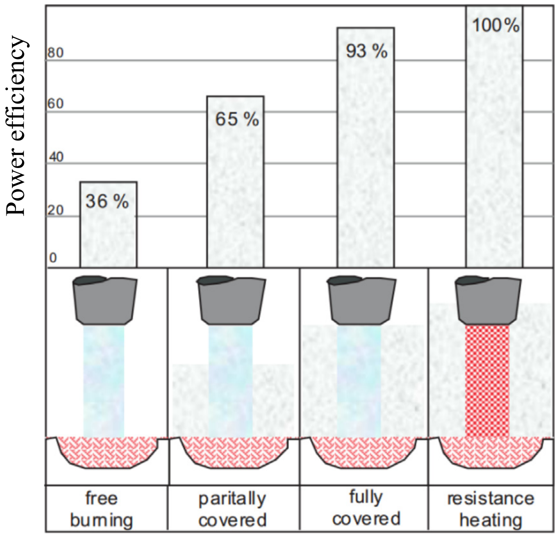

Fig. 1. Influence of foaming slag to the efficiency of power input [18].

The demonstration that a low-cost Hall effect-based sensor can be used for indirect measurement of the stability arc in an accurate manner will reduce the cost for implementing arc stability control methods which are expensive and intrusive currently requiring redesigning and technical electrical installation. This is of great importance specially for already existing EAF furnaces that can benefit from current sensor.

Based on these premises, this work validates a new low-cost and non-intrusive sensor that, measures the magnetic field magnitude and orientation in the furnace's proximities and analyses the acquired signal providing an arc stability factor metric (*Arc Stability Index*). This Arc Stability Index has been validated against other existing measurement alternatives (acoustic sensor, slag, bath computer vision-based inspection, expensive commercial fault detection system) with better or similar performance. The sensor has been integrated on existing DC and AC EAFs demonstrating a power reduction of 6.7 kWh per Liquid steel ton during the evaluated period and a time reduction of 1.1 min per heat.

The paper is organized as follows. In Section 2, we provide the theoretical concepts with regards to magnetic fields and Hall effect sensors. Sections 3 describes the design of a 3D Hall sensor based on three different 1D Hall sensor components. Section 4 defines mathematically the proposed *Arc Stability Index*

This *Arc Stability Index* is compared against the response of three different alternative measurement techniques (acoustic sensor, slag, bath computer vision-based inspection, expensive commercial fault detection system) where high correlation is obtained. Section 6 proposes a control algorithm based on the Arc Stability Index and validates the energy savings of the proposed sensor and Arc-Stability Index when used to regulate two DC and AC EAFs on real production settings. Finally, Section 7 concluding remarks are provided.

2. Magnetic field measurement

Let I_{arc} be the current flowing through the conductor that generates the arc in the EAF, D the distance from the measurement place and μ_o, the magnetic permeability of free space, the magnetic field generated on a point in the space is then defined by Eq. (1):

$$B = \frac{\mu_o \cdot I_{arc}}{2\pi D} \tag{1}$$

Magnetic field measurement ranges from simply sensing the presence or change in the field to the precise measurements of a magnetic field's scalar and vector properties. One of the methodologies used for magnetic field relies on the Hall effect. The Hall-effect sensor is based on the discovery of Edwin H. Hall in 1897. The Hall effect is a consequence of the Lorentz force law, which states that a moving charge (***q***) in an electric field (**E**), when acted upon by a magnetic induction field (***B***), will experience a force (***F***) that is at right angles to the field vector and the velocity vector (***v***) of the charge as expressed by the Eq. (2):

$$\overrightarrow{F} = -q(\overrightarrow{E} + \overrightarrow{v} x \overrightarrow{B}) \tag{2}$$

This principle has been applied in the development of Hall-effect sensors which are activated by an external magnetic field ***B***. If a Hall sensor powered by a voltage ***E*** is placed on a magnetic field, a voltage V_{out} proportional to the product between the powering current and the intensity of the normal component to the magnetic field ***B*** with respect to the sensor appears (Fig. 2).

In this work we have selected a sensor (A1302) with a high magnetic sensitivity which provides a voltage output that is proportional to the incident magnetic field perpendicular to the sensor orientation according to Eq. (3):