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Control of Non-Ferrous Electric Arc Furnaces

Benoit Boulet,
Vit Vaculik,
Geoff Wong
Hatch
2800 Speakman Drive
Mississauga, Ontario,Canada
L5K 2R7

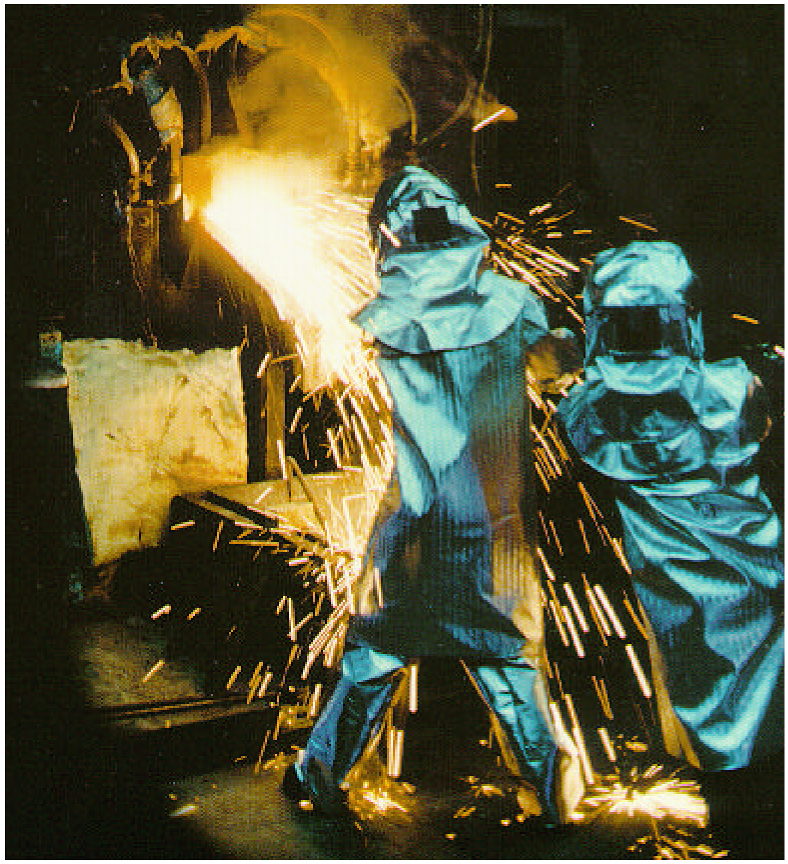

Figure 1: Matte tapping on an experimental DC furnace

Abstract

An important aspect of non-ferrous metal production is the separation process known as smelting, in which the concentrated ore is melted and separated into two components of different densities: the slag and the matte. The smelting process is carried out through high-power heating in electric arc furnaces.

In order to maintain a constant desired matte production rate and constant matte and slag temperatures, the average furnace power must be accurately controlled and coordinated with the concentrate feed rate. This paper presents power control technologies for high power smelting furnaces. Power quality and management issues are also briefly discussed.

Résumé

Un des aspects importants de la production de métaux non-ferreux est le procédé de fonte, dans lequel le minerai concentré est amené à son point de fusion dans une fournaise. Le minerai en fusion se sépare ensuite en deux composantes de densités différentes: les scories et le métal. Le procédé de fonte est mis en fonction à l'aide d'une fournaise à arc électrique de haute puissance.

De façon à maintenir un taux de production de métal constant et à obtenir des températures de métal et de scories constantes, la puissance moyenne de la fournaise doit être asservie de manière précise et coordonnée avec le taux de chargement du minerai concentré. Ce texte traite de technologies de commande de puissance pour fournaises de fonte à haute puissance. La gestion de la puissance électrique ainsi que sa qualité sont aussi discutées brièvement.

Introduction

Many of the most important players in the non-ferrous metal industry are Canadian companies with extended worldwide operations. These companies are involved in all aspects of metal production, from exploration and mining to metal refining and processing.

An important aspect of non-ferrous metal production is the separation process known as smelting, in which the concentrated ore is melted and separated into two components of different densities: the slag and the matte, the latter usually being the product. The smelting process is carried out through high-power heating in electric arc furnaces [4]. These furnaces are typically powered by three-phase AC substations capable of providing high currents to the furnace electrodes. The two most common electrode configurations for these AC furnaces are: three vertical electrodes positioned at the apexes of a triangle, each of which being connected to a phase of the transformer; and six in-line vertical electrodes, each pair of which being connected to a single-phase transformer, fed from one of the three phases of the main substation transformer. New technologies using DC power supplies are also emerging for non-ferrous ore smelting. Recently, pilot DC furnaces with a single hollow electrode have been tested [3]. Concentrate fines are fed through the electrode in these furnaces for fast smelting in the DC arc plasma.

In order to maintain a constant desired matte production rate and constant matte and slag temperatures, the average furnace power must be accurately controlled and coordinated with the feed rate [1]. Furnace power regulation can be achieved by varying the electrode positions in, or relative to, the bath through controlled electrode movements, in such a way that the resulting change in impedance will bring the furnace power closer to its setpoint. Power regulation is typically implemented with cascaded phase impedance and power feedback controllers.

This paper discusses classical and novel power control technologies for three-electrode and six-electrode AC furnaces. The development of a power quality analyser for real-time monitoring of harmonics and flicker generated by electric arc furnaces [5] is also briefly discussed.

Process

Smelting

The smelting process is essentially continuous, which imposes particular constraints on its control. For example, the furnace electrodes are consumed at a certain rate, and must be replaced after a while, or have sections continually being added.

The feed system must also support the continuous nature of the smelting process in the furnace. Feed rate control is necessary to keep the furnace around its optimal equilibrium of material content. Slag tapping can be considered as a quasi-continuous process in some smelters where the tap hole may be left open 80% of the time. On the other hand, matte tapping is essentially a batch process because ladles are used to convey the matte from the furnace to the converters.

Three-Electrode Furnaces

Three-electrode furnaces usually have a circular shape with an outer diameter varying from a few meters, up to 30 meters. These furnaces feature three vertical electrodes arranged in a triangular manner, each of which being connected to a phase of the three-phase furnace transformer secondary (see Figure 2). The primary of the furnace transformer can be either connected in star, or delta configuration. In star configuration, a neutral is typically connected to hearth ground straps which make contact with the molten metal and provide a ground for the electrodes. On the other hand, in a delta configuration, the matte bath essentially becomes a floating neutral.

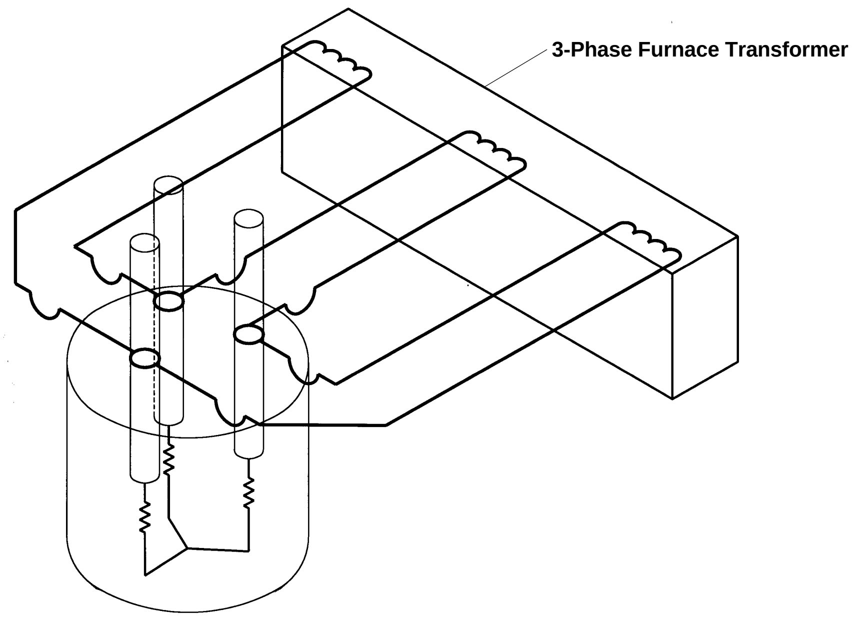

Figure 2: Three-electrode furnace circuit diagram

Typical power levels for three-electrode furnaces range from 10 MW to 80 MW, with electrode currents varying between 10 kA and 60 kA, and electrode voltages ranging from 100 V to 2000 V. Figure 3 shows a photograph of an arcing electrode tip in a furnace.

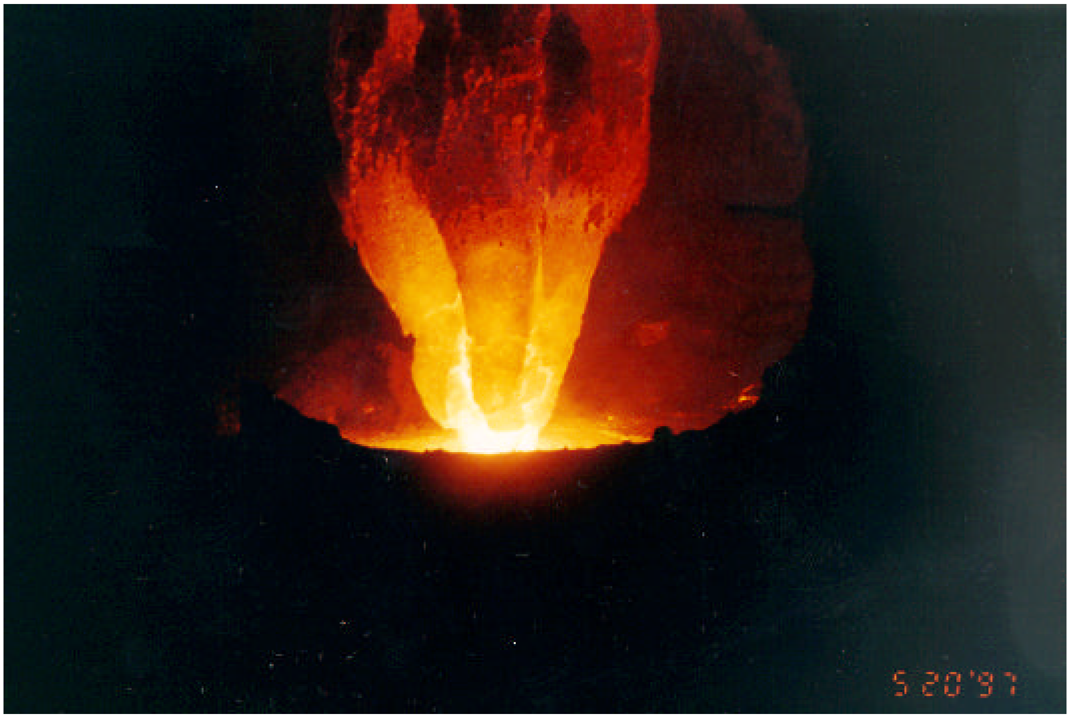

Figure 3: Arcing electrode tip in a furnace

Process Electrical

For a three-phase furnace transformer with multiple taps, the relationship between furnace power, tap voltage, and electrode current can be displayed on a so-called PVI chart, similar to the one shown in Figure 4 for a six-electrode furnace. This chart contains all the relevant information to specify furnace operating points for desired range of production rates. Typical data shown on PVI charts include: electrode current versus power curves for every tap voltage, for star and delta connection of the transformer's primary; electrode impedance curves; and transformer limits represented as an "envelope" superimposed on the curves. Note that three single-phase transformers may also be used to supply power to a three-electrode furnace.

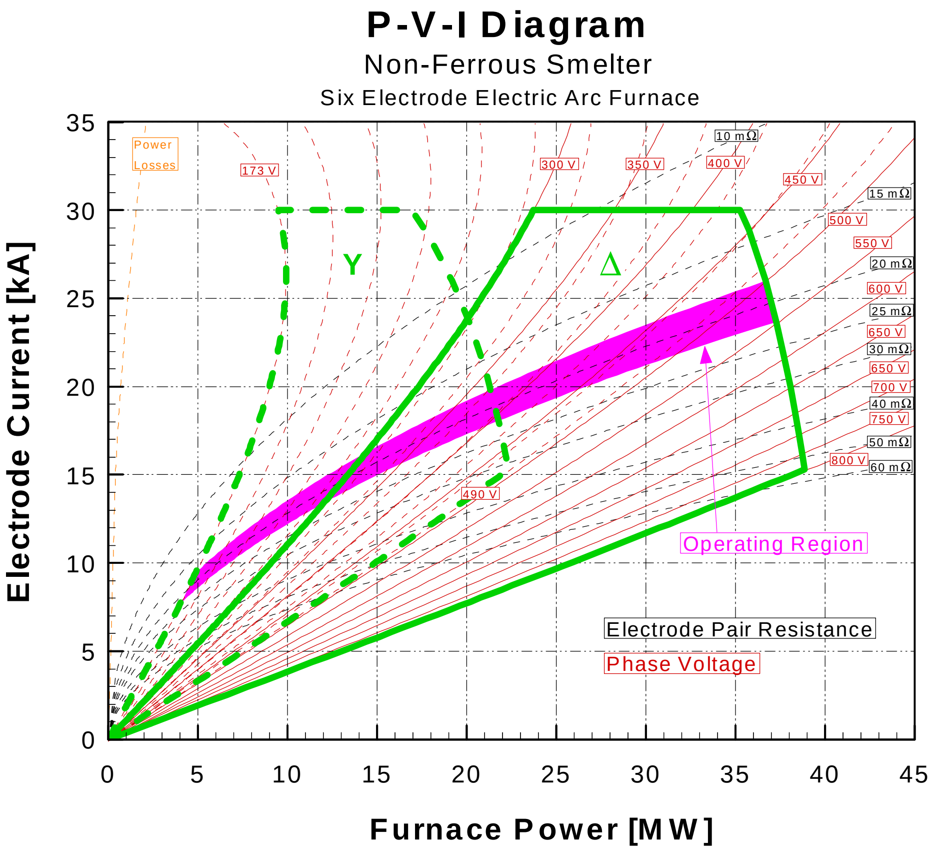

Figure 4: PVI chart for a six-electrode furnace

A furnace power setpoint is selected based on the desired matte smelting rate. Recent furnace transformers have on-load tap changers that are controllable from a computer. Thus, a tap or an impedance setpoint is usually specified by the operator along with the power setpoint. The control computer takes care of calculating which transformer tap will give the impedance closest to the setpoint, and it will typically run the tap changer to reach the calculated tap while ramping the power up or down.

Six-Electrode Furnaces

Six-electrode furnaces have six in-line electrodes, with each of the three electrode pairs connected to a phase of the power system. Three single-phase transformers, one for each phase, are typically used for six-electrode furnaces (Figure 5).

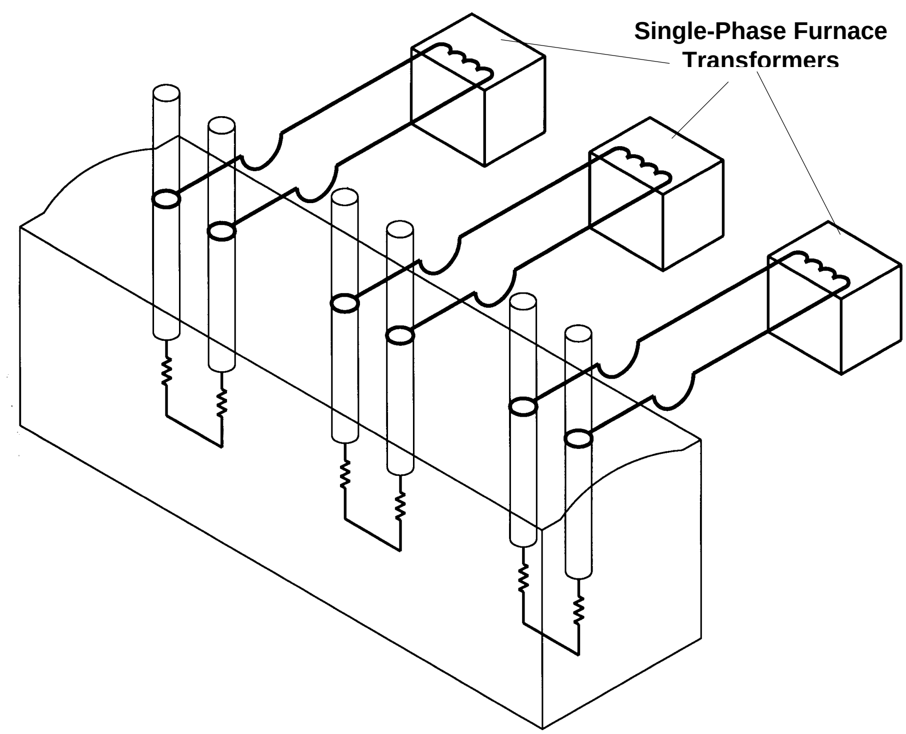

Figure 5: Six-electrode furnace circuit diagram

These furnaces have a rectangular shape with the matte tap holes at one end, and the slag tap holes at the other end [4]. Their sizes vary from 10 m X 5 m, up to 35 m X 15 m, depending on the required throughput and the type of ore concentrate. The largest of these furnaces can smelt more than a thousand tons of concentrate per day.

Process Electrical

For each single-phase furnace transformer with multiple taps, the relationship between phase power, tap voltage, and the current flowing in the electrode pair can be displayed on a phase PVI chart (Figure 4). The transformer limits are represented as an "envelope" superimposed on the curves.

Each phase power setpoint is calculated as a fraction of total furnace power, and they need not be balanced. For example, it may sometimes be required to put less than one third of the total furnace power on an electrode pair close to a tap hole. Running the furnace only on one phase is also feasible, although this would cause severely unbalanced currents, which may cause overheating of three-phase motors feeding off the same medium voltage bus as the furnace.

For each phase, the control computer takes care of calculating which transformer tap will give the impedance closest to the setpoint, and it will typically run the tap changer to reach the calculated tap while ramping the power up or down.

Control

The control of electric arc furnaces is based on the relationship between phase resistance and electrode immersion, or arc length.

Arcing operation

For a furnace operating in arcing mode, the resistance of the arc partly governs the amount of power released inside the furnace. Although chaotic in nature, the arc resistance may be thought of being roughly proportional to its length. Figure 6 shows a typical representation of a load resistance vs electrode immersion relationship. Arcing occurs for “negative” immersion of the electrode tip. Thus, the fundamental principle of impedance and power control is based on the phase resistance variations caused by moving the electrode up and down, which controls the arc length.

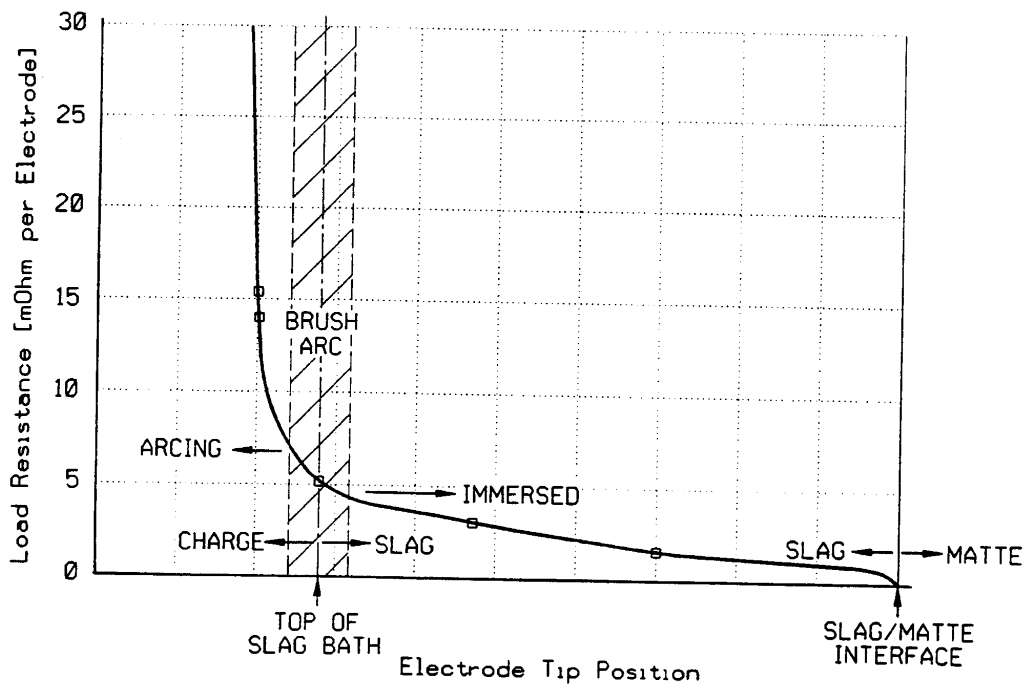

Figure 6: Electrode resistance versus electrode immersion

In an ideal steady-state operation, the phase impedance and power would be constant for a fixed electrode position. However, disturbances caused by concentrate feeding, arc instability, varying slag chemistry, tapping, waves in the bath, etc., cause large, fast variations in both phase impedance and power in open loop. Hence, feedback control is necessary to reject the effects of these disturbances, and regulate the average phase impedance and power to desired setpoints (Figure 7). When a loss of arc occurs on a three-electrode furnace, half of the total furnace power is lossed due to the three-phase circuit configuration. On the other hand, a loss of arc on a six-electrode furnace results in a power drop of only one third of the total furnace power.

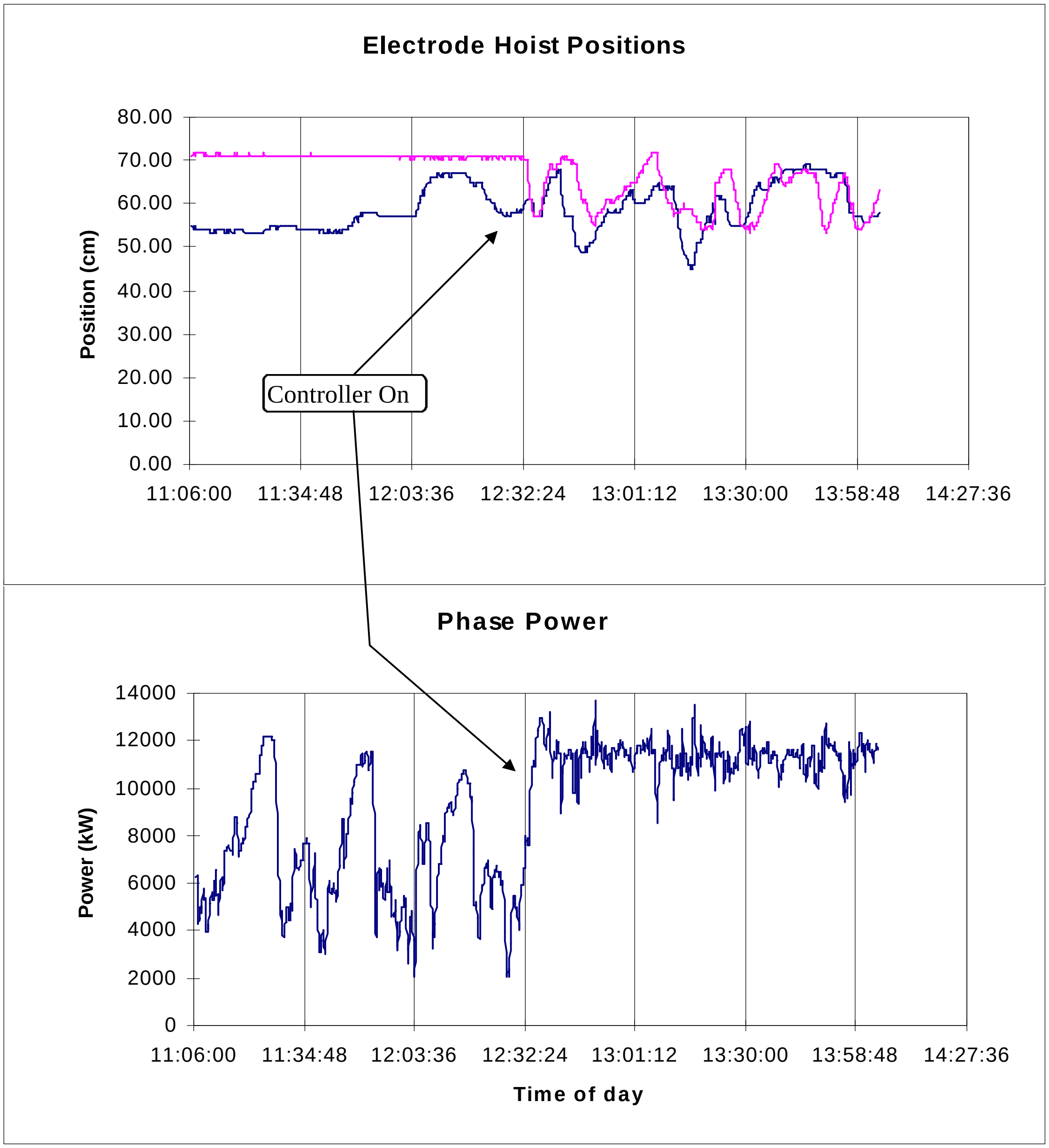

Figure 7: Phase power without, and with control

Immersed electrode operation

The resistance of the slag between the tip of an electrode and the slag-to-matte interface decreases as the electrode is immersed deeper into the slag, until it eventually vanishes when the tip reaches the matte. This variation in resistance depending on electrode immersion is the fundamental principle for impedance and power control (Figure 6) in immersed mode.

As previously mentioned for an open arc operation, ideally the phase impedance and power would be constant for a fixed electrode position in steady state. But model uncertainty and process disturbances make feedback control necessary to regulate the average phase impedance and power to desired setpoints.

Joule heating through the slag leads to intrinsically more stable impedance and power trends than open arc heating. On the other hand, a furnace running in arcing mode operates at higher voltages and lower currents, which reduces electrode consumption and allows higher furnace power for a given current limit. See [4] for a more detailed account of the pros and cons of different modes of arcing operations.

Control Strategy

For a fixed transformer tap, a cascade controller with the inner loop controlling the electrode impedance, and the outer loop controlling the phase power, is used in most cases. A cascade phase controller for a six-electrode furnace is depicted in Figure 8. The control signal actuates a valve or an electric drive that move the electrodes via hydraulic or electric motor-driven hoists.

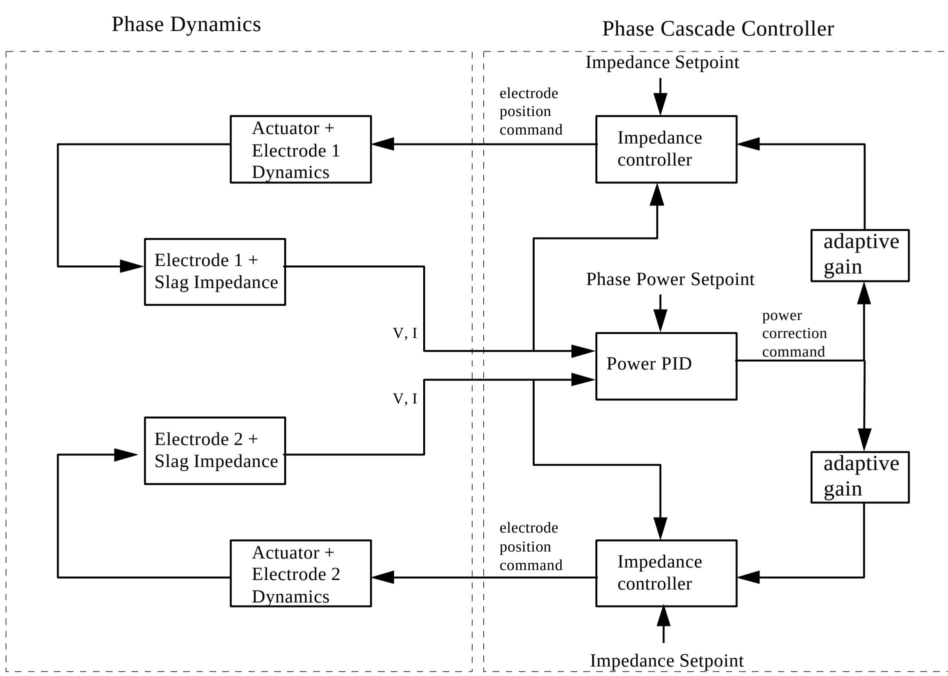

Figure 8:Cascade phase power controller for a six-electrode furnace

The control systems for three-electrode or six-electrode furnaces do not differ much.

However, the control of six-electrode furnaces is simplified by the electrical decoupling of each electrode pair fed by a single phase. For these furnaces, it is possible to control the power accurately on a single phase by moving the two corresponding electrodes. Movements of the other electrodes will not affect the phase power, provided they do not generate waves in the bath. This allows the furnace power control system to achieve good performance with three independent power/impedance cascade controllers.

On the other hand, three-electrode furnaces possess inherent couplings in the electrode currents due to their circuit topology. For instance, if only one of the electrodes is moved, all three electrode currents will change simultaneously. The current couplings make the impedance and power control of three-electrode furnaces more difficult. Novel decoupling techniques are currently under development to address this problem. Nevertheless, provided care is taken in their designs, cascade-type controllers have been shown to work on three-electrode furnaces as well.

Electrode Slipping

Two types of electrodes that are commonly used in electric arc furnaces are Soderberg electrodes, and graphite electrodes. Soderberg electrodes are made of a hollow steel shell filled with paste that bakes once it enters the furnace. Cylindrical steel sections (or cans) are welded on top of the electrode before adding the paste. A hoist system, with a stroke of roughly one to two meters, holds the electrode above the furnace and provides a dynamic range for electrode movement used for impedance and power control. A slipping mechanism mounted on the hoist slips the electrode, i.e., moves the electrode downwards relative to the hoist by a fixed short amount. Manual slipping requires that the operator monitor the average hoist positions, and initiate a slip sequence when a hoist is too close to its lower limit.

Traditional manual slip timers that initiate electrode slipping are usually not synchronized with electrode consumption, which is mainly governed by electrode current. Therefore, the electrodes may be consumed either faster or slower than the slipping rate, which causes them to migrate out of their controllable region. For instance, power and impedance control is lost when an electrode hoist bottoms out, which has been observed to occur frequently in some smelters. An electrode slipping controller is a new technology that automatically slips the electrodes whenever required, without the need for operator intervention. Apart from can welding which is still performed by human welders, a slipping controller renders the furnace power control fully automatic and allows continuous operation of the furnace.

Feed Control Systems

Feed systems are an integral part of the non-ferrous smelting process; they provide a continuous supply of material to the furnace. The material is typically a preprocessed mineral ore blended with some additives to enhance the smelting process. The primary objective of the feed system is to maintain a black-top layer in the furnace to insulate the molten bath. This increases smelting efficiency, which increases production. It also reduces the temperature in the area above the bath, known as freeboard, which reduces the deterioration of the furnace roof and off-gas system. Control of these material handling systems is critical in maintaining optimum production.

A recent implementation of a furnace feed control system was part of an overall feed system upgrade that provided the furnace with a distributed feed system. The control system was implemented on a PLC. The system utilized an air slide with pneumatically actuated diverter gates to each of the feed ports. Feed distribution control, which determines the amount of feed delivered to each feed port on the furnace, was implemented by the sequencing logic controlling the diverter gates. The sequencing logic incorporated dead time compensation to account for the transport delay inherent in a feed system of this type. Feed rate control was implemented using a variable speed feeder under feedback control; the feedback signal was the rate of change in weight as measured by load cells in the feed bin. The feeder speed was adjusted to compensate for any error between the actual and target feed rates.

As feed systems are an integral part of the smelting process, feed system control is very much an integral part of the overall plant process control. Supervisory control functions that coordinate furnace power control and furnace feed control ensure that the two systems work together. For example, a recent implementation of a feed control system coordinated the target feed rate with the power consumption through the use of feedforward compensation. In other feed system experience, the power setpoint and the feed rate were linked with a model so that the setpoint for one is determined by the other.

Energy Management Systems

Power Grids

Plant smelters are typically connected to a power grid which is regulated by a provincial utility. The energy contract between the utility and the plant operations usually contains the following items: an energy cost ($/kWh), a peak energy penalty (where the plant is charged additional funds when excessive energy is consumed during peak hours), and a power factor penalty (where the plant is charged when the power factor falls below acceptable levels). The peak energy and power factor penalty clauses in the energy contract may account for a significant amount of the total energy costs. In these cases, an energy management system would make-up or shed various plant loads such that an adequate power level is maintained during peak hours. Also, the energy management system would monitor real-time power factor readings and modify plant operations to minimize the power factor penalties.

Captive Generation Systems

Furnace power make-up and shedding greatly impacts a captive generation system because the majority of a plant's load is typically the furnace(s) [2]. Large variations in furnace power can result in plant load and frequency instability, and could easily damage a set of generators. The generators are directly affected because a captive generation system is usually geographically remote, and only has a single source of energy (e.g., hydroelectricity). Therefore, it is especially important that the furnace controller regulates the power levels in a captive generation system.

In addition, most smelter operations have multiple furnaces that can have varying power levels. Where one furnace may cause some damage to the generators, the net effect of multiple furnace power fluctuations can jeopardize an entire power generation facility.

Power Quality

Power quality throughout an entire plant, or an entire region, may suffer due to the operation of electric arc furnaces. Electric arc furnaces are very nonlinear loads due to the chaotic nature of arc impedance. Nonlinear loads are the principal cause of power quality problems including voltage dips, harmonic distortion and flicker. In a typical smelter, the medium voltage bus is connected to furnace transformers that deliver power to the arc furnace. As a result, other loads connected to the medium voltage bus and below are subjected to the effect of negative sequence and harmonic currents caused by the furnace. Under certain conditions, depending on the state of the distribution system, it may happen that the poor power quality gets also reflected to the power grid and other utility customers.

Power quality monitoring and control is a growing area of interest as utilities are starting to impose more constraints on smelter operations. The development of a power quality analyser [5] has been motivated by the need to provide a means of monitoring power quality to guide furnace operation, not only to minimize penalties, but also, to provide records for aid in negotiating power contracts with utilities. As recording intervals can span days to weeks for power studies, or months for overall operation monitoring and billing, efficient data recording methods are essential. Complete power management requires that enough quality data be stored to be meaningful, but not to be so excessive such that studying the data is too time consuming to be practical.

Conclusion

We have described three and six-electrode AC electric arc furnaces for non-ferrous ore smelting, with a special emphasis on their control requirements. Specific issues associated with furnace power and impedance control were discussed. A control strategy involving setpoint selection on PVI charts, automatic tap changing, and the implementation of cascade controllers was outlined. The continuous nature of the smelting process was shown to lead to special control requirements for peripheral furnace subsystems such as slipping and feed systems. Finally, the impact of electric arc furnace loads on power quality and stability was discussed, and partial solutions in the form of energy management systems and monitoring systems were outlined.

Future directions in furnace control technology include decoupling control for three-electrode furnaces, fuzzy-logic gain scheduling and control, flicker control, robotic tappers and can welders, and automated maintenance systems.

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