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# CPC Power Theory for Analysis of Arc Furnaces

***Abstract*** *— Electric Arc Furnaces (EAFs) are facilities with an intensive use of energy where small improvements in their control imply significant electrical energy savings. The electric arcs are highly nonlinear and chaotic; a power theory for non-sinusoidal voltages and currents is needed for the analysis of the EAFs. The Current´s Physicals Components (CPC) power theory allows an advanced engineering analysis of the energy transfer at arc furnaces since each one of the current components can be used as performance indicators to improve EAFs power control.*

***Streszczenie.*** *Piece łukowe są bardzo nieliniowe i chaotyczne dlatego są bardzo trudne do analizy. Wykorzystanie teorii CPC (Current Physical Components) umożliwia bardziej dokładną analizę przenoszenia energii i poprawę sterowania mocą.* ***Wykorzystanie teorii CPC do analizy pieców łukowych***

**Keywords**: Electric Arc Furnace, Power Control, CPC Power Theory
**Słowa kluczowe:** piec łukowy, teria CPC, sterowanie mocą

## Introduction.

Arc furnaces contribute to one third of the world´s steel production. EAFs are thermo-processing units using electric arc discharges as source of heat capable of melting scrap and ferrous metals trough heat transfer phenomena of conduction, convection and radiation [1, 4]. This heat source requires an intensive use of electrical energy and is combined with other chemical energy sources like natural gas and carbon [2].

In alternate current (AC) furnaces the power system is composed by a power transformer with variable tap and sometimes a series reactor on the primary side to increase the system reactance. The three AC arcs burn between the bases of the electrodes, which are arranged in a triangle (delta), and the scrap or steel bath. While the arcs are burning the electrodes wear down [1]. The electric arcs are controlled by electrode displacement. The objective of an arc regulation system is to drive up and down the electrodes to control a desired current or impedance per each phase. EAFs generate flicker, harmonic distortion and power system imbalance [5].

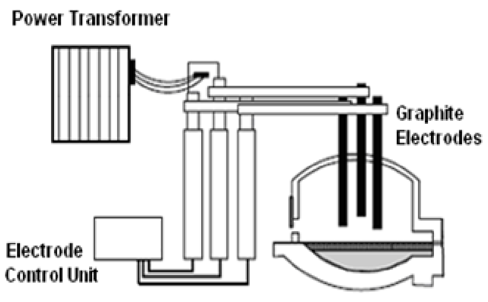


Fig. 1. Alternate Current Electric Arc Furnace.

Due to the non-linear nature of the electric arcs, the electrode current has a nonlinear relation with the arc voltage [2, 3]. The voltage at the arcs can be modeled, in spite of its non-linearity, as a sum of harmonic voltages according with Fourier analysis [3]. The harmonic distortion varies trough the heat process from higher total harmonic distortion (THD) at initial bore-down and early melting and it decreases during melting to a final lowest THD value during refine and heating stages. The amount of harmonic generation is therefore dependent on the stage of the melting process [5].

A relevant operational concept in arc furnaces is the arc stability. For steelmakers arc stability is associated with the continuity of the current in the sense that the arc does not extinguish in time [7]. Arc stability is estimated by measuring and processing the harmonic content of the transformer´s secondary side phase to ground voltages or line currents, the arc stability is often considered as a process variable to improve EAF power control.

## Arc Furnace Electrical Circuit.

The arc furnace is a three phase three wire system with very large electrical non-linear and time-varying loads. In this type of electric load the inductive part is not the only responsible for the shift of the transformer secondary fundamental current, the voltage-current non-linearity characteristic of the arc also contributes to the current shift. In spite of simplicity the EAF electrical circuit can be modeled as a combined resistor-reactor phase loads connected in delta, as depicted in Fig. 2, where $X_{arc}$ and $R_{arc}$ represent the arc impedances, $X_f$ and $R_f$ represent the furnace impedances (cables, arms and electrodes) and $X_t$ and $R_t$ represent the power transformer´s secondary side impedances.

The operational power level of an AC-EAF is given by the power system reactance from the point of common coupling to the electrodes tips and can be modified by changing transformer or reactor tap positions and by setting the current or impedance reference to the arc regulation system. At the measurement points the rate of energy deliver from the power transformer to the electric arcs is given by Eq. (1), (2) and (3):

(1) $$P_{\mathrm{EAF}} = \sum_{p=\mathrm{R,S,T}} \left[\frac{1}{\tau}\int_0^{\tau} u_{pg}\, i_p\, dt\right]$$

(2) $$P_{\mathrm{loss}} = (R_{\mathrm{f}}) \cdot \sum_{p=\mathrm{R,S,T}} \left[\frac{1}{\tau}\int_0^{\tau} i_p^2\, dt\right]$$

(3) $$P_{\mathrm{arc}} = P_{\mathrm{EAF}} - P_{\mathrm{loss}}$$

where: $u_{pg}$ - phase *p* to ground feeding voltage, $i_p$ - phase *p* instantaneous line current, $R_{\mathrm{f}}$ - furnace resistance, $\tau$ - period of the AC cycle.

For each of transformer tap (or tap combination with the step up transformer or primary tap reactor for installations where exists), there is a related power curve that can be obtained using the short circuit impedance. In Fig. 3 it can be seen how there are two power curves, one for the furnace transformer, $P_{EAF}$, and other for the electric arcs, $P_{ARC}$. It can be show how the voltage, $U_{ARC}$, and displacement power factor decrease with an increase in the electrode current. It is not defined how to determine the current, $I_2$, for the maximum energy efficiency (minimum electrical losses, $E_{EL}$).

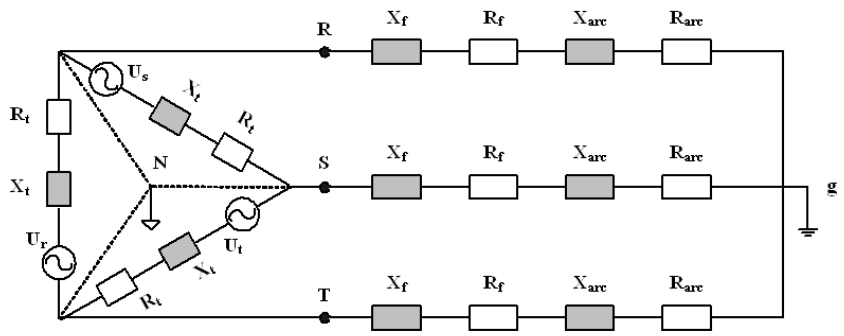


Fig. 2. EAF circuit model.

Identification of EAF power curves is common engineering practice to define operational points in current or impedance for a given transformer tap or transformer and reactor tap combination. Power profiles or power programs are used to apply different power levels during the heat process and they are often designed using the power curves. The operation criteria followed by most arc furnaces is to speed up the melting and heating process by using the highest possible average power (maximum power of the furnace transformer, $P_{EAF}$).

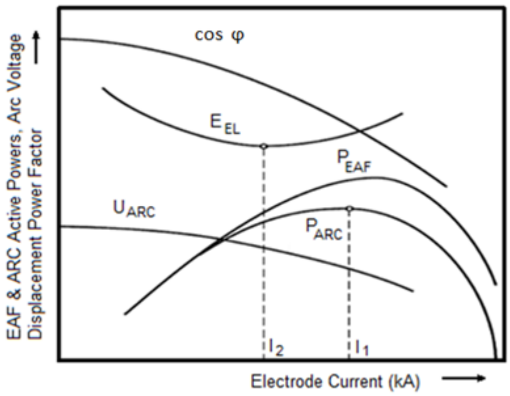


Fig. 3. EAF Typical power curves [2].

**Reasons to apply CPC Power Theory in Arc Furnaces.**

The main problem when an electrical engineering analysis is done in EAFs is that once the furnace is put in operation a chaotic operational reactance appears and this time varying reactance is higher than the short circuit reactance used in the definition of the original parameters, therefore the active power, reactive power and power factor are randomly fluctuating and they differ from their original design values.

At Arc furnaces there is a need for a power theory to be used for processing and monitoring the electrical parameters, and to control and optimize the electrical energy transfer. The 1459-2010 IEEE power definitions provide means to decompose the power and can help to monitor the power at the primary and secondary sides of the furnace transformer, but it does not provide means to identify the energy flows neither to correlate them with different physical phenomena occurring at the arc furnace. The instantaneous p-q power theory is precise only for balanced load conditions therefore it is not applicable to arc furnaces.

The CPC power theory gives orthogonal current components of the electrodes currents. If the electrode current can be mathematically decomposed to exhibit different related physical phenomena it has a major value for EAF analysis and control than other power theories. This study proposes the application of the Current´s Physical Components Power Theory for three-phase and three wire systems proposed by Czarnecki [8..10] because it present several advantages over other power theories:

- The use of more precise definitions for apparent power and a true power factor are relevant for EAF since they are intrinsically related to energy losses and efficiency.
- For arc furnaces, a current decomposition is more useful than power decomposition since the electrode current is a critical process variable required to be optimally controlled.
- Each one of the current´s physical components of the furnace electrical circuit could be correlated to process conditions to be used as process variables for the power control.

**Preliminary considerations to compute CPC Power Theory at EAF.**

The CPC power theory for three-phase three-wire systems considering load unbalance and harmonics generated by the load is the main subject of this analysis. Considering $U_{Rg}$, $U_{Sg}$, $U_{Tg}$ are rms values of voltages: $u_{Rg}(t)$, $u_{Sg}(t)$, $u_{Tg}(t)$, there is a voltage quantity for the three phase system:

$$U_{3\mathrm{f}} = \sqrt{U_{Rg}^2 + U_{Sg}^2 + U_{Tg}^2} \tag{4}$$

n the same way considering $I_R$, $I_S$, $I_T$ are rms values of currents: $i_R(t)$, $i_S(t)$, $i_T(t)$, there is current quantity for the three phase system:

$$I_{3\mathrm{f}} = \sqrt{I_R^2 + I_S^2 + I_T^2} \tag{5}$$

The above equations can be applied under the condition that the sum of instantaneous values of all three phase voltages and all three phase currents equals zero at any instant of time, this is,

$$i_R(t) + i_S(t) + i_T(t) = 0 \tag{6}$$

$$u_{Rg}(t) + u_{Sg}(t) + u_{Tg}(t) = 0 \tag{7}$$

The Eq. (6) is always satisfied, since it follows Kirchhoff's law. Eq. (7) needs to be carefully analyzed. Phase to ground measurements are typically available at arc furnaces. The bottom shell of arc furnaces is grounded and for this reason the secondary side of the power transformer is keep ungrounded, as it can be modeled in Fig. 2, therefore a virtual neutral point N is found at the supply side that has a fluctuating voltage with respect to the furnace ground g accordingly to the phase sequence, therefore the Eq. (7) is not satisfied and another set of phase voltages must be found.

For this study, the virtual neutral to ground voltage presented in [7] becomes relevant to obtain the set of balanced phase voltages required to process the CPC power theory. A set of balanced voltages can be deducted from the following equations:

(8) $$u_{Rg}(t) = u_{RN}(t) + u_{Ng}(t)$$

(9) $$u_{Sg}(t) = u_{SN}(t) + u_{Ng}(t)$$

(10) $$u_{Tg}(t) = u_{TN}(t) + u_{Ng}(t)$$

Adding the three phase voltages in the time domain in both sides of Eq. (10) yields:

(11) $$u_{Rg}(t) + u_{Sg}(t) + u_{Tg}(t) = u_{RN}(t) + u_{SN}(t) + u_{TN}(t) + 3u_{Ng}(t)$$

Since phase to virtual-neutral voltages have no zero sequence, they satisfy Eq. (12):

(12) $$u_{RN}(t) + u_{SN}(t) + u_{TN}(t) = 0$$

And Eq. (11) can be rewritten as:

(13) $$u_{Rg}(t) + u_{Sg}(t) + u_{Tg}(t) = 3u_{Ng}(t)$$

The virtual neutral voltage is obtained:

(14) $$u_{Ng}(t) = \frac{1}{3}\left[u_{Rg}(t) + u_{Sg}(t) + u_{Tg}(t)\right]$$

The implication of previous Eq. (14) is that the set of phase to virtual-neutral voltages can be determined by computing the virtual neutral to ground voltage ands subtracting it from the phase to ground measurements.

(15) $$u_{RN}(t) = u_{Rg}(t) - u_{Ng}(t)$$

(16) $$(t) = u_{Sg}(t) - u_{Ng}(t)$$

(17) $$(t) = u_{Tg}(t) - u_{Ng}(t)$$

Alternatively this set of balanced voltages can be measured using an artificial ground using potential transformers connected in a zig-zag configuration as shown in Fig. 4.

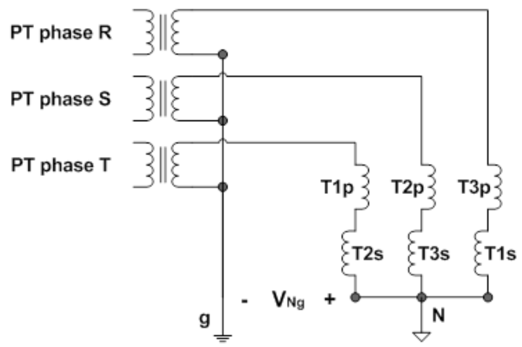


Fig. 4. Measurement of the phase to artificial ground voltages.

The arc furnace is supplied with a fundamental frequency, even though voltages and currents measurements at arc furnaces are not periodic in a formal sense. The concept of semi-periodic quantities [12] is applicable for the analysis of the EAF electrical parameters and this concept can be implemented with the actual digital signal processing systems. Considering the chaotic and non-linearity of the electric arcs, the running RMS values of current components can be filtered through moving averages and can be properly used for engineering analysis.

**EAF Electrical Energy Efficiency.**

In such a big loads like arc furnaces, small improvements in energy efficiency represent significant savings, this is why is so important to have correct definitions of apparent power, reactive power and true power factor. Unbalanced nonlinear loads like the arc furnaces can be considered as harmonic generating loads. To determine physical current components two set of current and voltage harmonics orders need to be determined to determine energy flowing to and from the electric arcs, the mutually excluding sets $N_{\mathrm{D}}$ and $N_{\mathrm{C}}$, are defined by the active power polarity:

(18) $$if\ P_{\mathrm{n}} \geq 0,\ n \in N_{\mathrm{D}}$$

(19) $$if\ P_{\mathrm{n}} < 0,\ n \in N_{\mathrm{C}}$$

Harmonics powers are then divided into two sets associated with the direction of the energy flow, from the supply source to the load, Eq. (20) and from the load to the supply source, Eq. (21). In this way it is possible to determine the amount of active power rejected by the arcs at some harmonic orders.

(20) $$P_{\mathrm{D}} = \sum_{n \in N_{\mathrm{D}}} P_{\mathrm{n}}$$

(21) $$P_{\mathrm{C}} = -\sum_{n \in N_{\mathrm{C}}} P_{\mathrm{n}}$$

The total active power $P$ is given:

(22) $$P = P_{\mathrm{D}} - P_{\mathrm{C}}$$

Accordingly to the previously identified energy flows, the load current can be decomposed into current $i_D$ responsible for energy flow from the power transformer to the electric arcs and current $i_C$ associated with energy flow in the opposite direction:

(23) $$i = i_{\mathrm{D}} + i_{\mathrm{C}}$$

They can be expressed as sum of harmonic current components:

(24) $$i_{\mathrm{D}} = \sum_{n \in N_{\mathrm{D}}} i_{\mathrm{n}}$$

(25) $$i_{\mathrm{C}} = \sum_{n \in N_{\mathrm{C}}} i_{\mathrm{n}}$$

The corresponding voltages $u_D$ and $u_C$, should satisfy the condition:

(26) $$u = u_{\mathrm{D}} - u_{\mathrm{C}}$$

They also can be expresses in terms of voltage harmonic components:

(27) $$u_{\mathrm{D}} = \sum_{n \in N_{\mathrm{D}}} u_{\mathrm{n}}$$

(28) $$u_{\mathrm{C}} = -\sum_{n \in N_{\mathrm{C}}} u_{\mathrm{n}}$$

The correct equation for apparent power according to the CPC theory is:

(29) $$S = \sqrt{S_D^2 + S_C^2 + S_E^2}$$

where:

(30) $$S_{\mathrm{D}} = U_{\mathrm{D}} I_{\mathrm{D}}$$

(31) $$S_{\mathrm{C}} = U_{\mathrm{C}} I_{\mathrm{C}}$$

(32) $$S_{\mathrm{E}} = \sqrt{U_D^2 I_C^2 + U_C^2 I_D^2}$$

In the case of the EAF, the apparent power definition that yields true power factor in the three-phase circuit is the following:

(33) $$PF = \frac{P_{\mathrm{D}} - P_{\mathrm{C}}}{\sqrt{P_D^2 + Q^2 + D_S^2 + D_U^2 + S_C^2 + S_E^2}}$$

The first advantage of the CPC Power theory is that it provides means to distinguish the power flow, meaning the energy transferred to the electric arcs. Fig. 5 shows a first current decomposition into current flowing to the electric arcs and vice versa. This decomposition is useful for a better monitoring of the energy transferred to and rejected by the arcs for each stage of the heat process. In this way CPC power theory helps for a better understanding of the energy transfer phenomena of the furnace electrical circuit.

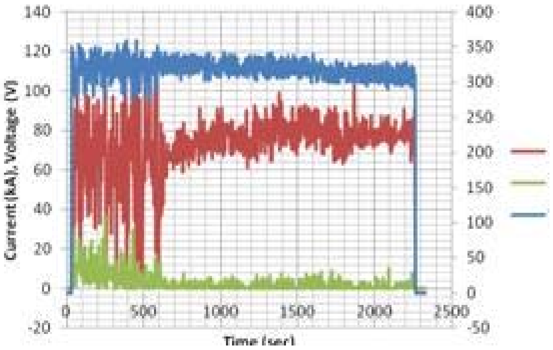


Fig. 5. Sets D and C of current phase R.

**Current versus power decomposition.**

In EAFs the main energy transfer is given by the fundamental current component and some energy is transferred back from the load to the power transformer because characteristic harmonics are imposed by the electric arcs, which are responsible for some part of the phase shift. Unlike in conventional inductive loads as transformers or motors, some energy losses in arc furnaces are dissipated not at the load but at the secondary side of the power transformer.

A correct definition for reactive and distortion power is crucial for EAF circuit analysis since a current setpoint must be chosen to operate the arc furnace at different stages of the heat. In this way, the electrodes current (line currents) are key process variables as they impacts the energy transfer and the electrodes consumption. Being the current a process variable it means it can be controlled by the modification of the current or impedance setpoint to the arc regulation system. In CPC theory the load current vector is compose of five vector components:

(34) $$\boldsymbol{i} = \boldsymbol{i}_a + \boldsymbol{i}_r + \boldsymbol{i}_s + \boldsymbol{i}_u + \boldsymbol{i}_C$$

where: $\boldsymbol{i}_a$: active current, $\boldsymbol{i}_s$: scattered current, $\boldsymbol{i}_r$: reactive current, $\boldsymbol{i}_u$: unbalance current, $\boldsymbol{i}_C$: load generated current.

The phase RMS values of these components satisfy the condition (per each phase, *R*, *S* and *T*):

(35) $$\|i\| = \sqrt{\|i_a\|^2 + \|i_r\|^2 + \|i_s\|^2 + \|i_u\|^2 + \|i_C\|^2}$$

Calculation the several current components, per each phase *R*, *S*, and *T*, over a complete heat results in obtaining useful process information. In Fig. 6 the current components are shown for phase R.

The meaning of the currents components is as follows: the active current is directly related to active power; the reactive power is related to reactive current; unbalance current is a consequence of the asymmetry in the load or furnace impedances; and, the remainder current can be classified depending on the direction of the harmonics energy flow to be scattered current or harmonic current generated by the load.

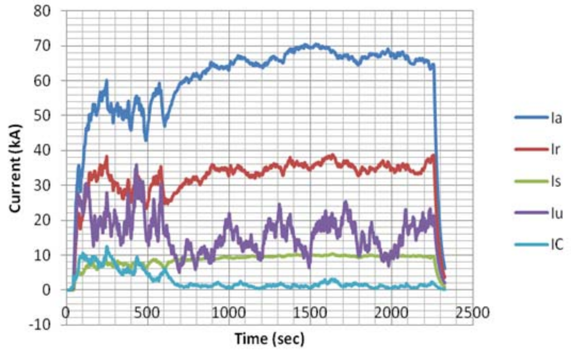


Fig. 6. Current components in a complete heat.

The current physical components of the electrode current can be used to detect either circuit or process conditions: The “active to electrode current ratio” is directly the phase power factor that already considers the harmonic distortion. The “reactive to electrode current ratio” can be used to determine the “furnace operational reactance”. These two components are the main parameters needed to be correctly chosen for the operation of the furnace at certain desired power.

In CPC power theory the power components can be obtained and expresses in terms of current components, in this way, the effort to process the EAF electrical signals (voltages and currents) in the frequency domain results in both current and power decomposition. The components of the apparent power $S_D$ are: Active power dissipated in the load, $P_D$, reactive power, $Q$, scattered power, $D_s$, and unbalance power, $D_u$:

(36) $$P_D = \|i_{\mathrm{a}}\|\|u_{\mathrm{D}}\|$$

(37) $$Q = \|i_{\mathrm{r}}\|\|u_{\mathrm{D}}\|$$

(38) $$D_S = \|i_s\|\|u_{\mathrm{D}}\|$$

(39) $$D_u = \|i_{\mathrm{u}}\|\|u_{\mathrm{D}}\|$$

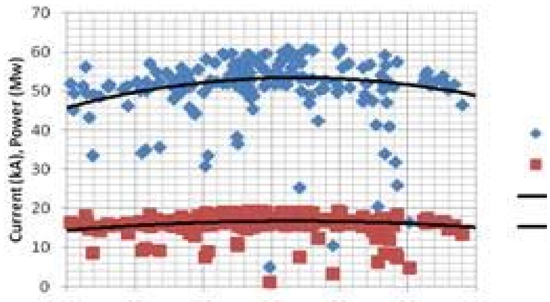


Fig. 7. Detection of peak active current and peak power.

Fig. 7 shows the active power and active current versus electrode current. Given such a loads as arc furnaces, where harmonics powers are flowing in both directions, a current decomposition is preferred for a better analysis of the energy transfer and as an engineering tool for properly selection of both current and voltage operational points for any given heat process condition.

**Current components as performance indicators.**

A better engineering analysis can be done if the current components are known, i.e. unbalance currents are process variables that can be potentially be used in arc regulation algorithms to mitigate the system imbalance and active and reactive current can be used to properly set the power operational level.

Even though further work is needed to correlate the current components to actual process conditions, some arc performance indicators like arc stability and arc coverage may be proposed in terms of the current components, for example, a detailed examination of the current decomposition over an entire EAF heat (see Fig. 6) reveals that at the beginning of the heat process, initial bore in and during unstable melting, some of the the non-active currents have wider fluctuations, later during stable melt and refining these current components gets lower variances. Therefore, it can be deducted that the values of the load generated and unbalance currents decreases throughout the heat process as the arc becomes less random and more stable.

The scatter current generated, in counterpart, is more stable and maybe more related to characteristic harmonics of the electric arcs than with the arc stability infringed by the melting or heating process. The dynamical change in its value may be related to other arc conditions, like the arc being slag covered or free burning. In this way different arc conditions and heat stages can be correlated with the amplitude and variance of both scattering and load generated currents.

In summary, in the case of arc furnaces, each one of the current´s physical components can be used as EAF performance indicators accordingly to the following reasons:

- Active current indicates the proportion of the electrode´s current that is delivering energy to the electric arcs.
- Reactive current is mainly due to the phase shift by furnace circuit reactance and by the arcs behaving as variable resistances.
- The scattered current indicates how the electric arcs disperse some of the electrode´s current at each of the harmonic orders.
- The load generated current measures the amount of harmonics currents imposed by the arc to the power transformer secondary windings.
- Unbalance current is mainly a consequence of the asymmetry present at the electric arcs or the transformer secondary circuit impedances.

**Conclusion.**

The current and power decomposition proposed by Czarnecki in his CPC power theory gives a comprehensible framework to better understand the power phenomena inside the EAF electrical circuit and can help to understand some relevant process conditions. The CPC theory is a suitable power theory not only for the analysis but eventually for power control of arc furnaces. Advantages of CPC Power can be summarized as follow:

- Provides correct definition for apparent power, true power factor and a treatment of harmonics powers that helps to determine which power are flowing to and reflected by the electric arcs.
- A current decomposition is more useful for the definition of operational points in current and power and to mitigate each on the non active current components.
- The scattered and harmonic generated by the load currents can be used in the definitions of arc stability indexes or arc slag coverage indexes.

Many further studies and experimentation could be and should be done in order to apply this advanced power theory for the power control and optimization of arc furnaces.

REFERENCES


[1] Muhlbauer A., Von Starck A. and Kramer C., Handbook of Thermoprocessing Technologies: Fundamentals - Processes - Components - Safety, Vulkan-Verlag GmbH, 2005

[2] Toulouevski Y. and Ziburov I., “Innovation in Electric Arc Furnaces”, Springer-Verlag Berlín, 2009.

[3] Bowman B. and Krüger K., “Arc Furnace Physics”, Verlag Stahleisen, Düsseldorf, 2009.

[4] Dittmer B. and Krüger K., “Theoretical approach to modeling thermal radiation in electric arc furnaces”, Electro-Heat International, Vol. 4, (2009), pp. 195.

[5] Beites, L. F., Mayordomo, J. G., Hernandes, A. and Asensi, R. (2001). Harmonics, Interharmonic, unbalances of arc furnaces:a new frequency domain approach, IEEE Transactions on Power Delivery, 16(4), 2001, 661-66

[6] Miller T.E., “Reactive Power Control in Electric Systems”, Wiley, Hoboken, NJ, 1982.

[7] Martell F., Deschamps A., Mendoza R., Meléndez M., Llamas A. and Micheloud O., “Virtual Neutral to Ground Voltage as Stability Index for Electric Arc Furnaces”, ISIJ International, Vol. 51, No. 11, (2011), pp. 1846.

[8] Czarnecki L., Currents’ Physical Components (CPC) in Circuits with Nonsinusoidal Voltages and Currents – Part 1: Single Phase Linear Circuits, Electric Power Quality and Utilization Journal, Vol. XI, No.2

[9] Czarnecki L., Currents’ Physical Components (CPC) in Circuits with Nonsinusoidal Voltages and Currents – Part 2: Three-Phase Three Wire Linear Circuits, Electrical Power Quality and Utilization Journal Vol. XII, No.1, pp. 3-13

[10] Czarnecki L.,, Currents’ Physical Components (CPC) concept: a fundamental of Power Theory, Przegląd Elektrotechniczny, R84, No. 6/2008, pp. 28-37.

[11] Czarnecki L.S., Working, reflected and detrimental active powers, IET on Generation, Transmission and Distribution,(2012) Vol. 6, No. 3, pp. 233-239

[12] Czarnecki L., Circuits with Semi-Periodic Currents: Main Features and Power Properties, ETEP Vol. 12, January/February