Virtual Neutral to Ground Voltage as Stability Index for Electric Arc Furnaces

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This article proposes an arc stability index for Electrical Arc Furnaces (EAF) based on the real-time processing of the line to ground three-phase voltage measurements typically available at the secondary side of the EAF’s power transformer. This methodology uses the definition of a virtual neutral for the open delta connection to calculate the neutral to ground voltage waveform and its Root Mean Square value that can be considered in a simple formula as stability indicator of the arc itself and for the power delivery to the arc. This proposed stability indicator may be used for process monitoring and power control.

KEY WORDS: Electrical Arc Furnace; EAF; arc stability index.

1. Introduction

Electrical Arc Furnaces are relevant to study because they contribute to a great portion (34% in 2010) of the world’s steel production. EAF facilities require an intensive use of electrical energy for scrap melting and refining into steel. EAFs generate severe power quality problems like flicker and power system unbalance and they require static var controllers (SVC) to mitigate power quality issues. The development of digital electronic instrumentation in applications of data acquisition systems made possible the real time processing of the EAF voltage and current measurements. Using digital signal processing techniques, like Fast Fourier Transforms (FFT), the spectral density and the total harmonic distortion (THD) can be obtained. There are commercial applications using either the THD or the variance of the THD as stability indexes for EAF process monitoring and control. This research work proposes a simpler, but novel, methodology to compute a stability index for detecting arc conditions inside the EAF. The proposed arc stability index does not require the frequency domain processing of the voltage measurement on the secondary side of the power transformer. It requires the processing of the three-phase voltages in time domain to calculate the virtual neutral to ground voltage, this RMS value it is proposed as an arc stability index that maybe used for EAF’s process monitoring and control.

2. Arc Electrical Behavior

2.1. Characteristics of the Electrical Arc

EAFs are thermo-processing units using plasma arcs as source of heat capable of melting scrap or direct reduced iron, DRI, trough the heat transfer phenomena of conduction, convection and radiation. This heat source is combined with the intensive use of chemical energy trough natural gas burners and carbon-oxygen lances. 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 power control, see Fig. 1. The three AC arcs burn between the bases of the electrodes, which are arranged in a triangle, and the bath, while the arcs are burning the electrodes wear down. Electrical arc is mainly controlled by an electrode control system. The objective of the arc regulation is to control a desired voltage-current ratio of the transformer secondary electrical parameters for a desired voltage tap. Electrode control systems can be hydraulic or winch drive. Figure 2 shows a simplified model of the arc as electrical load and Eq. (1) shows the calculation of the arc voltage based on this model.

\[ v_{arc,R} = v_{Rg} - R_l \frac{di_R}{dt} \]  

where,
- \( v_{arc,R} \) is phase R to ground arc voltage
- \( v_{Rg} \) is phase R to ground feeding voltage
- \( i_R \) is phase R line current
- \( R_l \) is furnace resistance
- \( L_f \) is furnace inductance

Fig. 1. EAF Power System.
The variable resistor can be modeled to obtain the voltage and current waveforms of Fig. 3 that correspond to the arc voltage and current reported in literature.2–4) Since the arc volt-ampere characteristic is nonlinear, the entire electrical circuit becomes non-linear as well.2) The harmonic currents are produced when the harmonic voltages from the arc are imposed across the electrode and furnace transformer and reactor impedances.5)  

2.2. Harmanics and THD as Arc Stability Index

For steelmakers arc stability is associated with the continuity of the current in the sense that the arc does not extinguish in time. Under this condition the current/voltage are reasonable symmetrical and high order harmonic content is low. Arc stability is estimated by measuring harmonic content of the transformer’s secondary side voltage or line current. Notice that the stability concept, referred in this article, is neither the plasma arc stability as defined in6,14) nor the stability of the electric power system, but it may have some relation with both of them. The electrical arc voltage can be modeled, in spite of its non-linearity, as a sum of harmonic voltages according with Fourier analysis.2) The harmonic distortion varies trough the heat process from higher THD at initial bore-down and early melting and it decreases during melting to a final lowest THD value during refine and superheating stages. The amount of harmonic generation is dependent on the stage in the melting process.7) The scrap melting generate predominantly third harmonic voltage and produce a very erratic total harmonic distortion (THD), especially early in the heat cycle when the electrodes are boring into the scrap steel. During refining the furnaces particularly generate third and fifth harmonic voltages and produce a less variable THD since the steel bath is already reached. Typical upper limits for the harmonic components during melting and refining stages are given in Table 1.8) In this table harmonics are given as a percentage of the fundamental arc voltage.

Since the arc voltage is complicated to measure, due to changes in position of the electrode, we have to use what is available at all EAF sites, these are the phase to ground voltages that are typically connected to potential transformers (PTs) and can be read with adequate voltage/current transducers. The arc stability is a practical indicator on how the arc is imposing harmonic distortion, this stability term is used for process monitoring and control. The level of power input into and arc furnace is principally dependent on the choice of transformer voltage tap, reactor tap and the current set-point.2) In EAF power system studies the arc stability is a relevant process variable to define operational points in power (transformer and reactor taps selection).9) Researching modern EAF Electrode Regulation Systems it can be found some applications using THD for arc stability and foaming slag indexes.10,11) It can be noticed that the arc stability is a key process variable that, in combination with the heat staging, defines the operational power level, like in the following example of a dynamic power profile using the stability calculated with the THD.10,11) In the melting process an initial power profile is defined, however, depending on the arc stability this profile has to be changed due to the fact that the system can’t deliver high power under unstable arc conditions. On the other hand, as soon as “stable arc conditions” are detected, power delivery can be increased (to reduce total heat time and increase productivity). Figure 4 shows how these changes take place during the heating process based in an analysis of the “arc stability”. It is seen that in A and C there is an increase in tap/power due to the fact of reaching good arc stability while in B the system/controller is forced to reduce tap/power due to bad arc conditions (poor stability). Notice that what is called stability index in Fig. 4 is in fact “instability index” since when the arc is working without any interruption and with almost pure sinusoidal current its value is the smallest in the heat.

3. EAF Three Phase Circuit

3.1. EAF Transformer’s Secondary Side Circuit

The electrical circuit seen from the secondary side of the EAF’s transformer is shown in Fig. 5. The power source (transformer) is ungrounded because the load (furnace shell)
is grounded. Most of the AC EAF installations have secondary winding delta connected and in a few cases wye ungrounded connection. In Fig. 5 Rsc and Xsc represent the short circuit parameters and Rf and Xf the furnace (cables, arms and electrodes) values.

3.2. EAF Voltage Measurements

Recent performed measurements of the three-phase to ground voltages are shown in Figs. 6 and 7. The voltage waveforms present harmonic distortion and unbalance what originates severe power quality issues on the primary side of the power system which is a characteristic of all electrical arc furnaces. These three voltage waveforms exhibit varying harmonic distortion depending of the stages of the heat process, as mentioned earlier, and it can be appreciated in the next two figures.

4. Proposed Stability Index

4.1. Virtual-Neutral and Phase to Neutral Voltages

The voltage behind source impedance (infinite bus) is balanced and sinusoidal. Before establishing the arc (zero current) when one electrode touches the scrap or steel bath, the corresponding phase voltage equals ground potential. This does not mean that phase voltage is short circuited, there is not line current due to the fact that the source is ungrounded. In order to ignite an electrical arc, at least two electrodes need to reach the scrap, or the slag/molten steel. Even if the transformer connection is delta, there is a virtual-neutral point, N (see Fig. 8), not physically available, but the neutral to ground voltage, \( V_{Ng} \), can be calculated based...
on measured values. This neutral point has been already considered in the mathematical modeling of electrical arc furnace,\textsuperscript{12)} and was already being detected in field measurements using phase equalizing resistors.\textsuperscript{13)}

With the proposed definition of a virtual-neutral point, the expressions for the phase to ground voltages are given in next equations where \( v \) denotes a time domain voltage, \( v(t) \):

\[
\begin{align*}
    v_{Rg} &= v_{RN} + v_{Ng} \quad \text{(2)} \\
    v_{Sg} &= v_{SN} + v_{Ng} \quad \text{(3)} \\
    v_{Tg} &= v_{TN} + v_{Ng} \quad \text{(4)}
\end{align*}
\]

Adding the three-phase voltages, in time domain yields:

\[
    v_{Rg} + v_{Sg} + v_{Tg} = v_{RN} + v_{SN} + v_{TN} + 3v_{Ng} \quad \text{(5)}
\]

Since phase to neutral voltages have no zero sequence, then:

\[
    v_{RN} + v_{SN} + v_{TN} = 0 \quad \text{(6)}
\]

Therefore the virtual-neutral to ground voltage can be calculated as:

\[
    v_{Ng} = \frac{1}{3}(v_{Rg} + v_{Sg} + v_{Tg}) \quad \text{(7)}
\]

If the virtual-neutral to ground voltage \( (v_{Ng}) \) is measured in a real heat process it can be found that its behavior changes through the entire heat. For bore-in and early melting the arc is rather “unstable” and it has higher distortion. Virtual-neutral to ground voltage tends, later in the heat, to get a lower harmonic distortion or what can be thought as a more “stable” condition for late melting and refine heat stages. Two waveforms of the virtual neutral to ground voltage are compared in Fig. 9. It shows the virtual neutral to ground voltage for the previous three-phase waveforms of Fig. 6 (early melting) and Fig. 7 (late melting). The \( v_{Ng} \) voltage has a strong component of third harmonic, as expected, and much higher harmonic distortion for early melting (unstable arc) than for late melting (stable arc). It is almost a \( 3 \times 60 \) Hz sinusoidal waveform.

Phase to virtual-neutral voltages can be computed, once virtual-neutral to ground voltage has been obtained, according to the following equations:

\[
\begin{align*}
    v_{RN} &= v_{Rg} - v_{Ng} \quad \text{(9)} \\
    v_{SN} &= v_{Sg} - v_{Ng} \quad \text{(10)} \\
    v_{TN} &= v_{Tg} - v_{Ng} \quad \text{(11)}
\end{align*}
\]

The processing to obtain the phase to neutral voltages implies filtering the neutral to ground fluctuations. Once processing the original phase to ground voltage measurements for early melting of Fig. 6, the phase to virtual-neutral voltages of Fig. 10 are obtained. It can be noticed that the virtual neutral to ground voltages are much less distorted than the phase to ground voltages.

If processing the “late melting” measurements of Fig. 7, the phase to virtual-neutral voltages of Fig. 11 can be obtained as well. If compared the phase to neutral computed voltages with the original phase to ground measurement it can be noticed that the processed voltages have almost no distortion and they are much more balanced.

4.2. Calculation of the Stability Index

Since this virtual-neutral to ground voltage has an intrinsic relation with arc condition through the entire heat, it can be useful to compute its root mean square (RMS) value.

\[
    V_{Ng} = \sqrt{\frac{1}{T} \int_0^T v_{Ng}^2 dt} \quad \text{(12)}
\]

This RMS value of the neutral to ground voltage (easily measurable) can be a process variable to be monitored for electrical arc furnaces and may be used as a performance indicator: With the RMS value of the neutral to ground volt-
age and the RMS value of the phase to neutral voltage calculations, a stability index can be proposed as:

\[ S_{\text{index}} = \frac{V_{\text{RNg}} + V_{\text{SNg}} + V_{\text{TNg}}}{V_{\text{RV}} + V_{\text{SV}} + V_{\text{TN}} + 3V_{\text{Ng}}} \]  \hspace{1cm} (13)

This ratio is a “direct proportional index” (higher index value for better arc conditions). This formula, with the value of the neutral to ground RMS voltage, gives a better idea on how the increase on this voltage affects the arc stability. The measurement and calculations of \( V_{\text{Ng}} \) and the proposed stability index were verified experimentally in a 160 ton EAF with a power transformer of 120 MVA.

5. Experimental Results

5.1. Experimental Setup

A Data Acquisition System was implemented using National Instruments LabView with NI-CDAQ-9172 hardware including specialized modules for electronic conditioning. The measurement of the EAF secondary’s side voltages and currents waveforms was performed at the TENARIS-TAMSA plant in Veracruz, Mexico. The connection points where the same for the three-phase voltage and current inputs that are used for the electrode arc regulation system (secondary side PTs and CTs.). It was possible to acquire 60 cycles per second for more than 20 heats using a second system, the ELSPEC’s G4500 that was connected in parallel to collect readings for post-processing. Tap 9 (943 V) is used for melting and Tap 8 (913 V) for final heating.

5.2. Data Measurement and Processing

Last bucket charge of the heat was selected for this analysis because it is when the different stages of the heat (bore-in, early melting, late melting and refine) occurs, and it is also when the arc gets its more stable condition. Phase to ground voltage total harmonic distortion is calculated by:

\[ \text{THD}_V = \frac{\sqrt{V_{\text{RNg}}^2 + V_{\text{SNg}}^2 + V_{\text{TNg}}^2}}{V_{\text{Ng}}} \]  \hspace{1cm} (14)

The neutral to ground RMS voltage \( V_{\text{Ng}} \) proposed in Eq. (12) is analyzed throughout the heat. A strong correlation is found with the THD value for each of the three-phase to ground voltages. Figure 12 shows \( V_{\text{Ng}} \) for a last bucket of one heat, it can be seen how this value compares with the THD of the phase to ground voltages (\( V_{\text{Rg}}, V_{\text{Sg}} \) and \( V_{\text{Tg}} \)).

The \( V_{\text{Ng}} \) RMS value is also given in the following equation:

\[ V_{\text{Ng}} = \frac{3V_{\text{Ng}}}{3} \]
\[ V_{Ng} = \sqrt{V_1^2 + V_2^2 + V_3^2 + \sum_{h=4}^{\infty} V_h^2} \]  

where,

- \( V_1 \) is the fundamental (60 Hz) RMS voltage
- \( V_2 \) is the second harmonic
- \( V_3 \) is the third harmonic
- \( V_h \) is the harmonic of order \( h \)

In Eq. (15) the harmonics of order \( 3k \) (\( k=1,2,3 \ldots \)) are present in balanced operation, the rest of the harmonics (3\( k+1 \), 3\( k-1 \)) are due to unbalance and instability. \( V_{Ng} \) can also be compared and analyzed in a scattered chart with the voltage THD of voltages \( V_{Rg}, V_{Sg} \) and \( V_{Tg} \). It can be seen in Fig. 13 that for lower range of \( V_{Ng} \) values (from 50 to 100 Volts) the THD increments are nonlinear and smaller than for higher values of \( V_{Ng} \) (above 100 Volts) where the relation is fairly linear. Further research will be done to analyze \( V_{Ng} \) fluctuations and find relationships with the changes in tap voltage, arc length, slag conditions and its correlation with THD. It can be stated that the stability index calculated with \( V_{Ng} \) is more sensitive to arc conditions than the ones calculated with the phase voltage THD.

Finally, Fig. 14 shows the calculation of the proposed stability index of Eq. (13) using \( V_{Ng} \) for a complete heat (2 buckets). This stability indicator is directly proportional to arc stability, hence to the power transferred to the EAF.

As seen before, both THD and the proposed stability calculation based on \( V_{Ng} \) are good indicators of heat stages and arc stability. However, there are two advantages in the new suggested stability index:

- \( V_{Ng} \) can be directly measured with a standard voltmeter and three resistors. THD requires complex calculations.
- A single voltage \( V_{Ng} \) is an indicator of the three-phase system behavior and power transfer to the heat.

6. Conclusion

This research article proposes the use of phase to ground voltage measurements in the time domain to calculate the virtual neutral to ground voltage and compute its RMS value to be used for calculating a stability index. This index could be used for process monitoring and additionally for power control at EAF facilities. It has two advantages over using THD indicators for arc stability: first, it is an easier calculation in the time domain while the THD requires FFT; second, the index calculated from virtual neutral to ground voltage and the phase to virtual neutral voltages is a stability indicator for the complete three-phase system and power delivered to the heat. This proposed indicator allows determine heat conditions and could be used in the future to design supervisory control systems to optimize EAF operations.

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