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REPORT OF INVESTIGATIONS/1994

Accurate Power Monitoring for Electric Arc Furnaces

By Alan D. Hartman and Thomas L. Ochs

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	ns	nanosecond
kHz	kilohertz	s	second
kW	kilowatt	V	volt
lb	pound	Ω	ohm
MHz	megahertz		

ACCURATE POWER MONITORING FOR ELECTRIC ARC FURNACES

By Alan D. Hartman[1] and Thomas L. Ochs[2]

ABSTRACT

Standard metering of electric arc furnaces usually uses root mean square (RMS) or true root mean square (TRMS) measurements for determining power. Only sinusoidal signals are accurately described by RMS meters, and dc or high-frequency components normally are lost in standard TRMS metering. This can lead to inaccuracies when electrical signals are not sinusoidal, contain dc components, or include fast risetime perturbations, as is the case with the electric signals from an electric arc furnace. Electric arc furnace electrical waveforms, observed in research carried out by the U.S. Bureau of Mines, show high-frequency components and significant deviations from sinusoids. These perturbations and distortions make metering difficult for standard power meters. The inaccuracies in metering can cause further problems if those sensors are used in control systems. For control strategies requiring rapid response, any averaging scheme loses information that can be used in control decisions. In order to obtain better signals for both monitoring and control, a study of instantaneous, RMS, and TRMS power monitoring devices was conducted. From this study it was concluded that precision integrated circuits should be used to obtain instantaneous power with a bandwidth of at least 25 kHz. The information from these devices is more representative than that of standard meters and can be used in predictive control.

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INTRODUCTION

The U.S. Bureau of Mines (USBM) is conducting research to improve operating efficiency and reduce electrical and acoustical noise in electric arc furnace (EAF) steelmaking. In the steelmaking process, small changes in efficiency or productivity can have a significant impact on marginal profit. To assess the effects of control strategies on power consumption in an EAF, it is necessary to measure accurately the true electrical power used. Standard power metering currently in use for monitoring the electrical signals from an EAF may not be accurate for measuring the nonsinusoidal electrical signals observed in this research.

Power meters measuring RMS (root mean square) information will be in error when the monitored signal is not sinusoidal. Brief introductory information on the RMS operation is presented below.

For any periodic function $Y_{(t)}$ with a period τ, the average value is given by

$$Y_{(av)} = \frac{1}{\tau}\int_0^{\tau} Y_{(t)}dt, \tag{1}$$

where $Y_{(av)}$ = average periodic function,

Y = time period,

and $Y_{(t)}$ = periodic function at time, t.

As an example, a waveform of the form $V = V_o \sin(\omega t)$ has an average value of

$$V_{(av)} = V_o \frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} \sin(\omega t)dt = -V_o\frac{1}{2\pi}\cos(\omega t)\Big|_0^{\frac{2\pi}{\omega}} = 0, \tag{2}$$

where $V_{(av)}$ = average voltage,

$V_{(o)}$ = initial voltage,

ω = angular frequency,

and π = pi.

To avoid this zeroing of symmetric functions and to give an idea of effective values, the RMS operation is applied. The RMS value of a function $Y_{(t)}$ with a period τ is given by

$$Y_{(RMS)} = \left[\frac{1}{\tau}\int_0^{\tau}(Y_{(t)})^2 dt\right]^{\frac{1}{2}}. \tag{3}$$

Again, using the waveform $V = V_0 \sin(\omega t)$ as an example, the RMS value is

$$V_{(RMS)} = \left[V_o^2 \frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} \sin^2(\omega t)dt\right]^{\frac{1}{2}}$$

$$= \left(\frac{1}{2}\right)^{\frac{1}{2}} V_o = 0.707V_o. \tag{4}$$

If a meter measures the RMS value as defined in equation 3, this is called a TRMS (true root mean square) value. However, many meters measure the average voltage and then correct that reading to RMS (*1*).[3] The correction value used is the ratio of the absolute average of a sinusoidal signal and the RMS sine value. The absolute average is obtained by taking the integral of equation 2 and effectively integrating over a half-cycle by changing the value of the signal to an absolute value. This yields

$$V_{(abs\ av)} = \frac{2}{\pi} V_o, \tag{5}$$

and the correction (cor) for average response meters is

$$cor = \frac{V_{(RMS)}}{V_{(abs\ av)}} = \left(\frac{\pi^2}{8}\right)^{\frac{1}{2}} \approx 1.11. \tag{6}$$

When measuring a square voltage waveform, an averaging meter will respond by multiplying the average absolute voltage for a cycle by 1.11, which will be 11% higher than the actual average value and the TRMS value (fig. 1). Other meters measure the peak voltage and assume a sine

[3]Italic numbers in parentheses refer to items in the list of references at the end of this report.

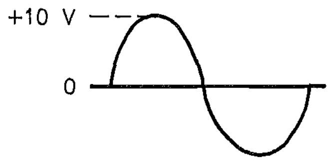
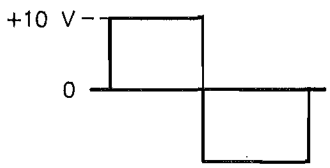
Waveform	Peak value	RMS value	Average responding meter	ac coupled TRMS meter	Averaging meter error
Sine 	10 V	7.07 V	7.07 V	7.07 V	0 %
Square 	10 V	10.00 V	11.10 V	10.00 V	11 %

Figure 1.—Power monitoring meter comparison results on sine and square wave.

wave input. They then correct the peak measurement by multiplying 0.707, which in the case of the square wave is almost 30% lower than the true average or TRMS value (*2*).

For more complicated, rapidly varying functions, the response of the meter is further limited by the electrical characteristics of the meter, such as crest factor and bandwidth. Crest factor is the ratio of the peak measurable value to the RMS value. This specifies the useful dynamic response range of a meter. For waveforms seen on experimental electric furnaces, meters capable of crest factors greater than 4 are necessary, although most meters have a crest factor of less than 2. Most industrial meters also have a band pass limited to less than 1 kHz. Both crest factor and bandwidth lead to errors in the estimation of the applied voltage. Even for relatively well-behaved systems, these problems can be significant (*3-4*).

Another aspect of integrated signals such as RMS measurements is that historical information in the waveforms is condensed to a single value. This value cannot be used to reconstruct the waveform that produced the single value since there are an infinite number of possible waveforms that could have produced that value. As an example, given a sine wave of amplitude $\sqrt{2}\ V_o$, a square wave of amplitude V_o, and a triangle wave of amplitude $\sqrt{3}\ V_o$, the RMS values are all V_o (fig. 2). While these waveforms all have a different form and will produce distinctly different results, the RMS values are all identical. It should be apparent that there is a considerable amount of information lost in the integration process. The results can become even more confusing when the waveforms are as complicated as those found in arc furnaces, as shown in figure 3. For these reasons the USBM has designed and built an integrated circuit that accurately measures power of any shape of electrical signal containing all components of the power spectrum from dc to the frequency limits of the individual solid-state devices.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

The 100-kW-rated 200-lb-capacity experimental EAF and equipment have been described in previous publications (*5-6*). The voltage electrical signal was acquired across a single arc, and the current was obtained from a 0.0001009-Ω, water-cooled shunt on the bus bars. These signals were monitored using a variety of power meters with different bandwidths and crest factors. A Valhalla 2101 power meter[4] (20-kHz bandwidth with a crest factor minimum of 2.5) (*7*) measured TRMS power, a Keithley multimeter (100-kHz bandwidth with a crest factor of 3) (*8*) measured instantaneous average power, and an

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

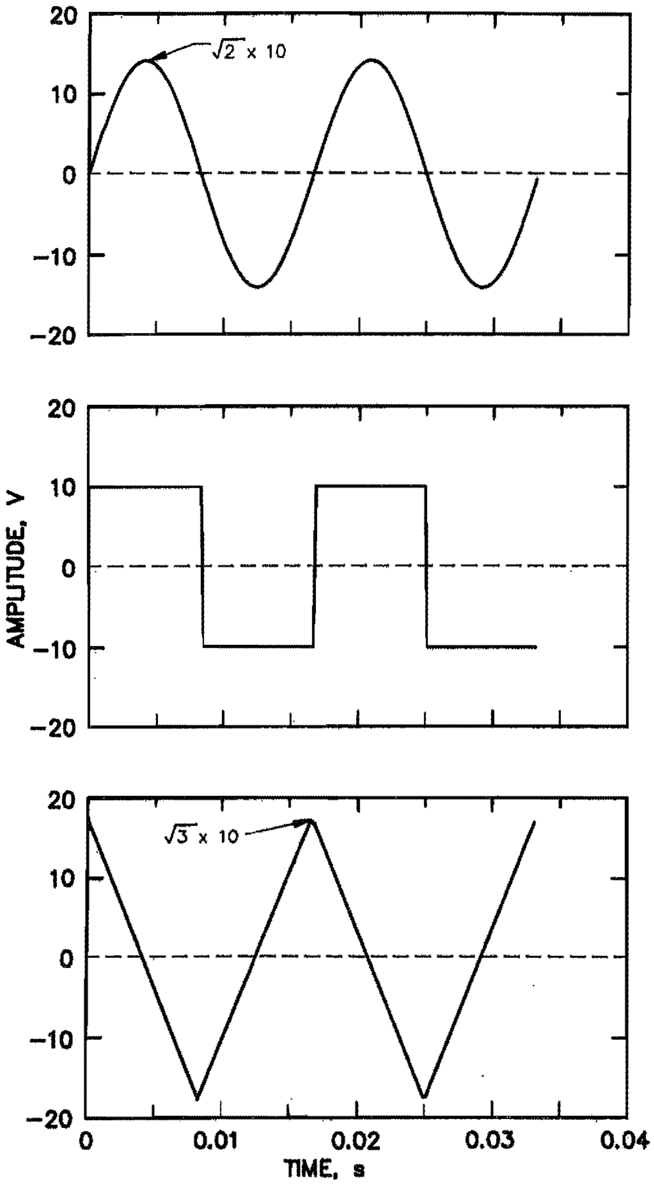


Figure 2.—RMS value comparison of sine, square, and triangle waveforms. The RMS value of 10 is identical for all three waveforms.

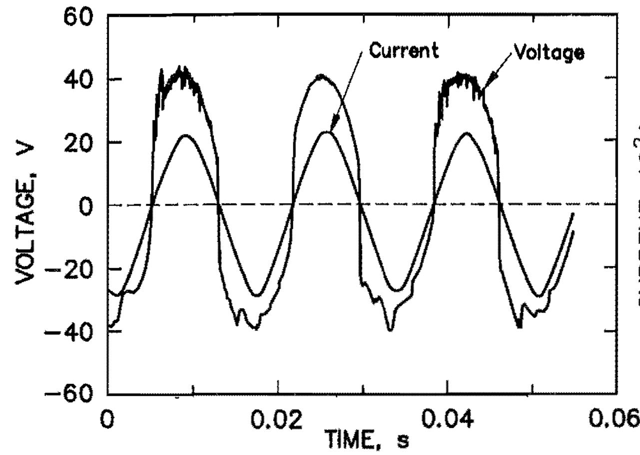


Figure 3.—Typical voltage and current waveforms from electric arc furnace.

integrated circuit was designed and built to measure TRMS power (200-kHz bandwidth with a crest factor of 10).

Figure 4 is a schematic of the USBM integrated power measuring circuit. The voltage signal, across the arc, was acquired from the bus bars and sent into a Philips isolation amplifier PM8940 (*9*). The isolation amplifier has a bandwidth of dc to 1.5 MHz and a risetime[5] of 230 ns. The isolation signal is then amplified 10 times with a precision instrumentation amplifier (AD524) (*10*, pp. 4-25 to 4-36) with a bandwidth of 400 kHz at the gain of 10. The current signal follows a similar path, originating from a water-cooled shunt on the bus bar and then through another isolation amplifier and an instrumentation amplifier with a gain of 10. Each signal then enters a separate high-precision wideband RMS-to-dc converter (AD637) (*10*, pp. 8-17 to 8-24) with a 200-kHz bandwidth that computes the TRMS value of any complex waveform. A crest factor compensation scheme in this integrated circuit chip permits measurements of signals with crest factors of up to 10 with less than 1% additional error. In this USBM system, analog output signals then are directed to an internally trimmed precision integrated circuit multiplier (AD534) (*10*, pp. 6-13 to 6-21) with a bandwidth of 1 MHz. The multiplied signal then either is available as an instantaneous power signal for control purposes or is converted to a digital signal by an analog-to-digital converter before storage on disk by a personal computer.

The power information from the integrated circuit closely matched the response of a commercial Valhalla TRMS power meter, as can be seen in figure 5. For

[5] The time required for the output signal to change from 10% of the input signal to 90% of the input signal.

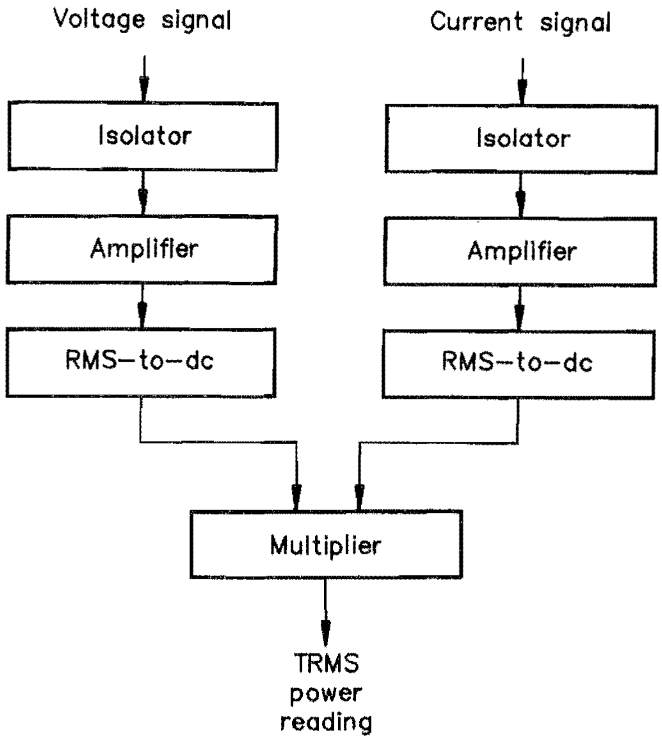


Figure 4.—Integrated circuit power measuring schematic.

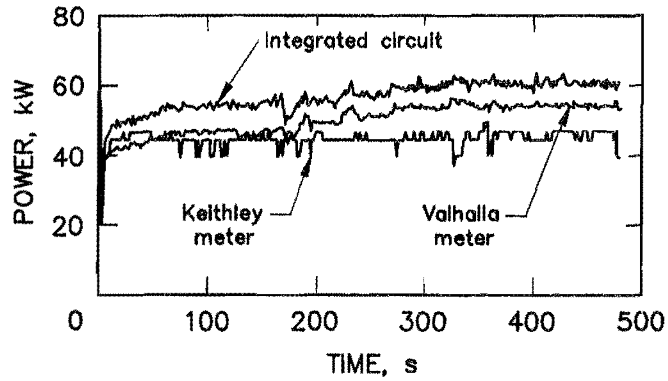


Figure 5.—Power trace comparison from integrated circuit, Valhalla, and Keithley power measuring devices.

comparison purposes, a Keithley multimeter was used to record the average (RMS) instantaneous power, which is shown as the lower trace in figure 5. This shows that most RMS power measuring devices are not accurate for monitoring distorted waveforms with rapid perturbations such as those occurring in EAF's. The power monitoring integrated circuit built and tested against standard power monitoring devices allows instantaneous and TRMS information to be acquired for any complex waveform.

RESULTS AND DISCUSSION

Typical voltage and current waveforms, shown in figure 3, show rapid, high-frequency perturbations in the signals that deviate from pure sinusoidal signals. These waveforms contain information on the behavior of the arc as a circuit element. From these waveforms, it is believed that control decisions can be made that use the rapid changes in the arc characteristics to predict occurrences a short time later. Therefore, instantaneous waveforms would be the best source to be measured for power and subsequent use in rapid control strategies for improving the performance of the EAF, rather than RMS information, which is the average of multiple ac cycles. Therefore, the application of an integrated circuit such as the USBM's for power monitoring is ideal for control schemes, since the information is instantaneous and has the attributes of a large bandwidth, a high crest factor retains original waveform information on which the power is based, and the circuit is relatively inexpensive. The integrated circuit chips used in the USBM's circuit were purchased for less than $40 per chip.

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