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Title: Power and Power Factor Measurements on the Induction Heating System at TA-46

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Power and Power Factor Measurements on the Induction Heating System at TA-46

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This report documents the results of a power and power factor measurement for an induction heating stystem at TA-46 was measured on 11/06/2013. The system setup is a powersupply running with a frequency of 23 kHz and 600 Hz connected through a power cable and a glovebox feedthrough to an induction heating coil. Figure 1 shows a schematic and the assumed electrical circuit that needed to be measured. As shown in the picture, a waveform of the amperage and voltage was recorded between the feedthrough and the induction coil. The feedtrough is referred to as the ancient feedthrough. The induction coil was loaded with a tantalum crucible.

In order to measure the power and power factor correctly, it is important to solve the following differential equation.

$$\dot{V} = L\ddot{I} + R\dot{I} + \frac{I}{C} \tag{1}$$

This equation can be solved in the case of a pure periodic voltage of

$$V(t) = V_0 cos(\omega t), \tag{2}$$

$$L\ddot{I} + R\dot{I} + \frac{I}{C} = -\omega V_0 sin(\omega t). \tag{3}$$

Since it is easier to solve this differential equation in a complex phase-space, one can substitue

$$V = V_0 e^{i\omega t}. \tag{4}$$

it is noteworthy, that the solutions only referred to a periodic voltage and current. By solving equation 1 the result of

$$I(t) = I_0 e^{i(\omega t - \varphi)} \tag{5}$$

is derived. To accommodate the result of the complex equation, a complex resistivity or impedance can be defined as

$$Z = \frac{V}{I} = \frac{V_0}{I_0}e^{i\varphi} = |Z|e^{i\varphi}. \tag{6}$$

Since Z can be displayed as a vector of length $\frac{V_0}{I_0}$ and an angle of the phase shift φ. The real component of Z is now the true resistance in the circuit wherease the imaginary component is considered the blind resistance of the circuit.

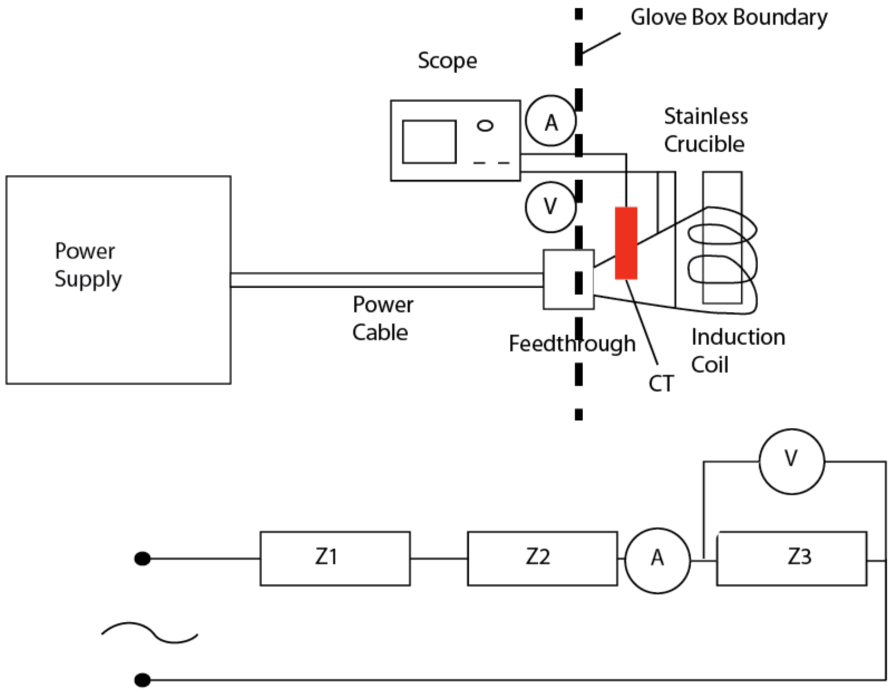

Figure 1: Schematic of the performed measurement and it's assumed circuit. The current and voltage was measured between the feedthrough and the induction coil. In the circuit diagram this translates to a measuring point between Z2 and Z3.

For the pure resistive circuit impedance is

$$Z = R. \tag{7}$$

For inductance the impedance can be calculated from equation 1 to be

$$Z = i\omega L. \tag{8}$$

in case of a capacitive circuit, impedance is

$$Z = -\tfrac{i}{\omega C}. \tag{9}$$

Impedances in serial configuration can be added whereas in parallel impedance circuits the conductivity is added:

$$Z = \sum Z_i \text{ (serial)}, \tag{10}$$

$$\frac{1}{Z} = \sum \frac{1}{Z_i} \text{ (parallel)}. \tag{11}$$

The actual measurements were conducted with a Tektronix digital phosphorescent oscilloscope. The oscilloscope had a math tool built-in to calculate power values. In addition wave-forms were digitized and analyzed to compare the measurements.

Current and voltage were measured as a function of time with an eight bit digitizer. Those platforms but then analyzed by creating values for true power and apparent power:

$$P_{\text{True}} = \overline{I(t)V(t)} \tag{12}$$

$$P_{\text{App}} = I_{\text{RMS}}V_{\text{RMS}} \tag{13}$$

$$\tag{14}$$

The power factor is defined as the ratio between between true and apparent power.

$$PF = \frac{P_{\text{True}}}{P_{\text{App}}} = cos\varphi \tag{15}$$

To extract the impedance of the measurements, the following formula for the impedance was used.

$$\vec{Z} = R + iX \tag{16}$$

The real part of the complex impedance $\vec{Z}$ is the resistance R and the imaginary part is the reactance X. The average power dissipated is related to the current And resistance through

$$P_{\text{True}} = I^2_{\text{RMS}}R \tag{17}$$

$$R = \frac{P_{\text{True}}}{I^2_{\text{RMS}}} \tag{18}$$

With these equations the power factor can be written as:

$$PF = \frac{R}{\|\vec{Z}\|} \tag{19}$$

$$= \frac{R}{\sqrt{R^2+X^2}}, \text{ which results in} \tag{20}$$

$$X = \sqrt{\left(\frac{R}{PF}\right)^2 - R^2}. \tag{21}$$

By applying this analysis, the power-losses were calculated. Table 1 displays the measured power, as well as the power values of the scope analysis. The measurements were conducted for two different power supplies a Radyne supply driving the circuit at 600 Hz and a power supply made by EFD (Engineered Fluid Dispensing) running at 23 kHz.

In addition to the measurement power factors, the digitized waveforms were analyzed individually. Figure 4 and figure 5 show pictures of the digitized waveforms. By finding the zero crossing of the waveform, the frequency was established, and according to the above equations, the power factors as well as the measured power output were calculated. As displayed in the graph of figure 2 the power operating the coil increases linearly with the powe supply output power. This is consistent with the graph in figure 3. It shows that the powerfactor for each power supply will not change across the input power spectrum.

Frequency	Power [KW] Supply	Power [KW] Scope	Power Factor Scope	Power [KW] Fluke	Power Factor Fluke	Power [KW] Claculated	Power Factor Calculated
600	10	5.60	0.18	5.70	0.20	5.08	0.18
600	8	4.50	0.18	4.80	0.21	4.04	0.18
600	6	3.10	0.18	3.20	0.19	3.06	0.18
600	4	2.10	0.18	2.40	-0.19	2.91	0.17
600	2	1.10	0.20	1.09	-0.21	1.06	0.20
23000	10	5.60	0.07	4.90	0.06	5.61	0.06
23000	8	4.70	0.06	3.60	0.05	4.71	0.06
23000	6	3.32	0.06	2.80	0.05	3.32	0.06
23000	4	2.15	0.06	2.00	0.05	2.15	0.06
23000	2	1.23	0.05	1.00	0.05	1.08	0.05

Table 1: Power and power factors calculated and measured by Scope and Fluke meter.

In summary, the three different measurements of the power and the power factor turn out to be very comparable to each other. The analysis varies by a maximum of $\pm 12\%$. As expected, the measured power output on the coil increases linearly with the power supply output.

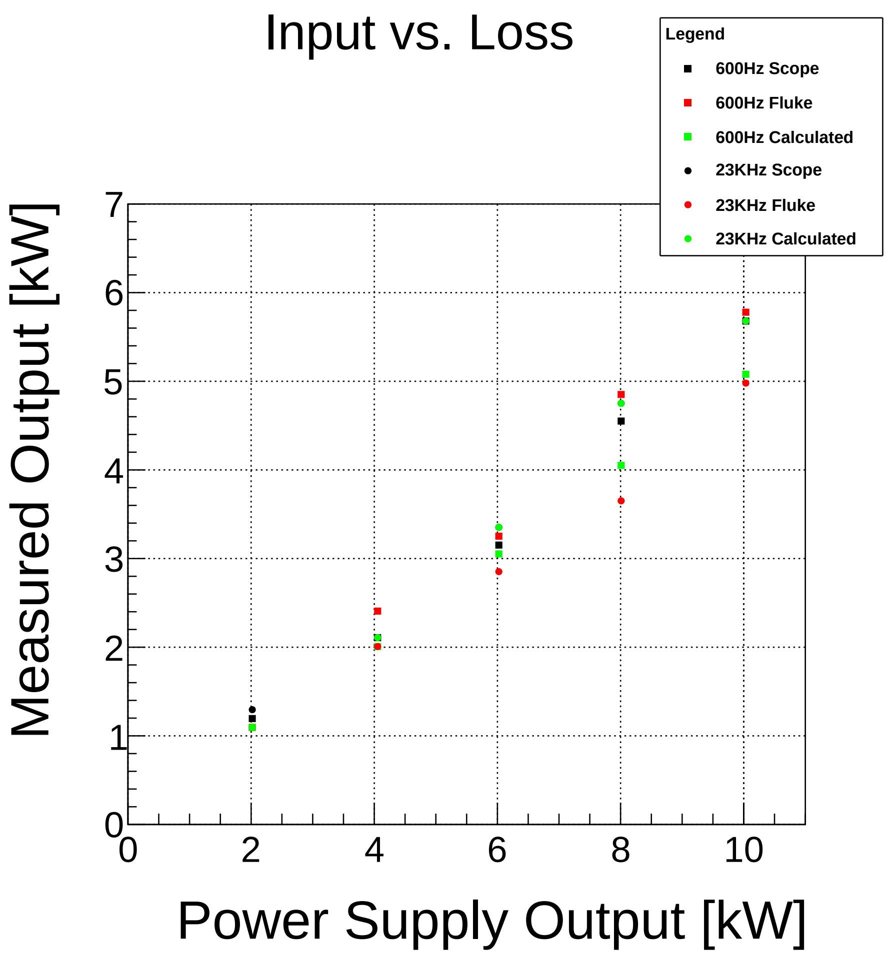

Figure 2: Power factors measured by the oscilloscope for differen input power at 600 Hz and 23 kHz.

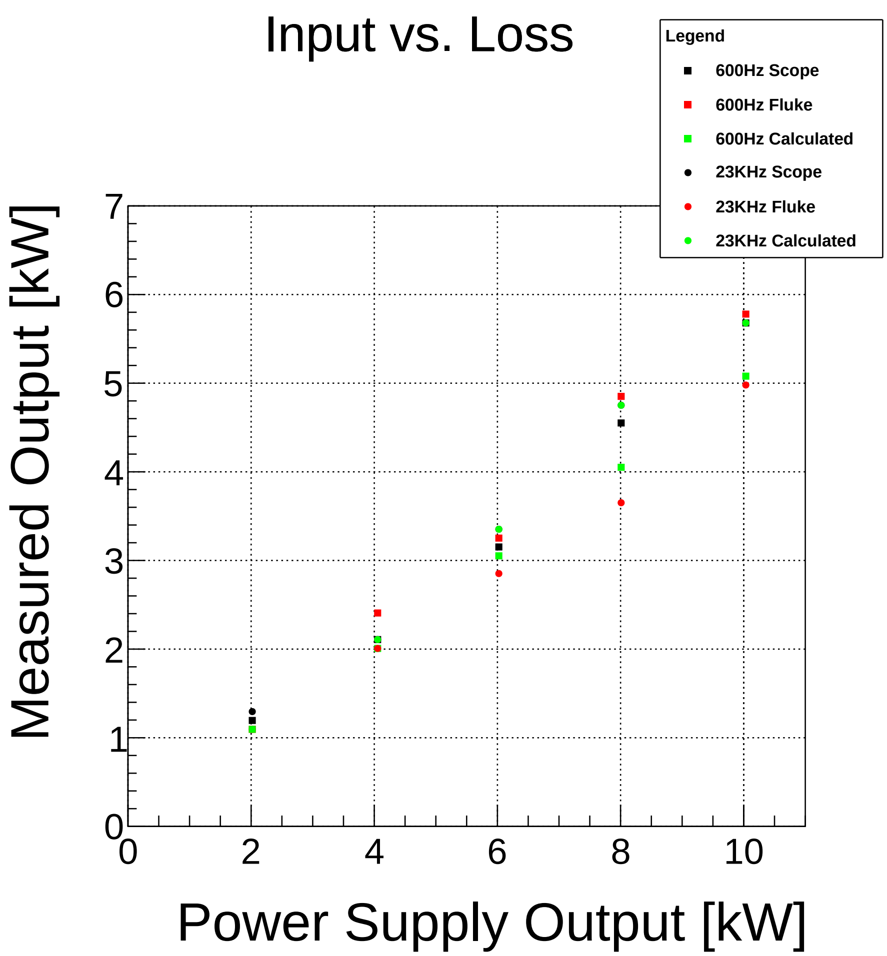

Figure 3: Power consumption at the coil versus power input from the power supply at 600 Hz and 23 kHz frequency.

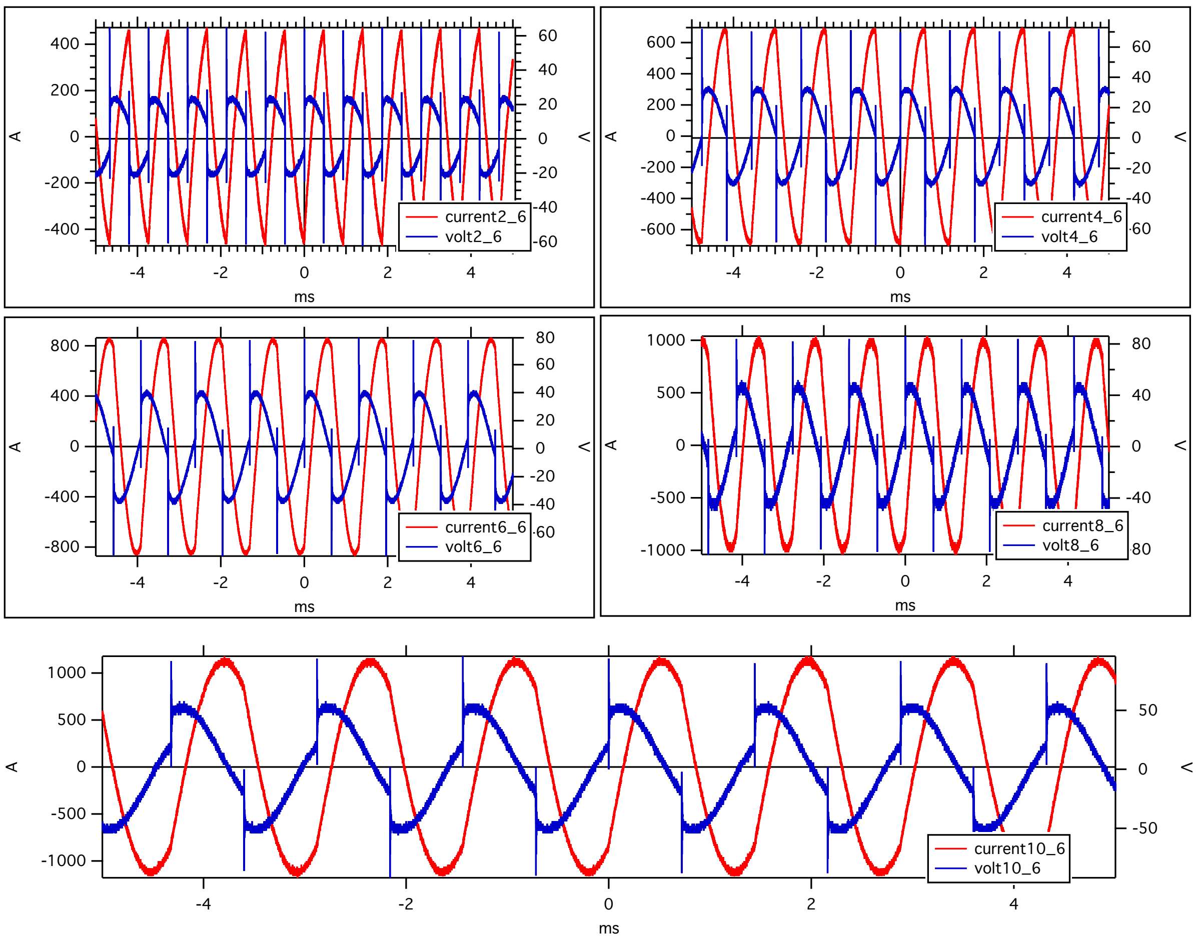

Figure 4: Display waveforms of all IV measurements at 600 Hz.

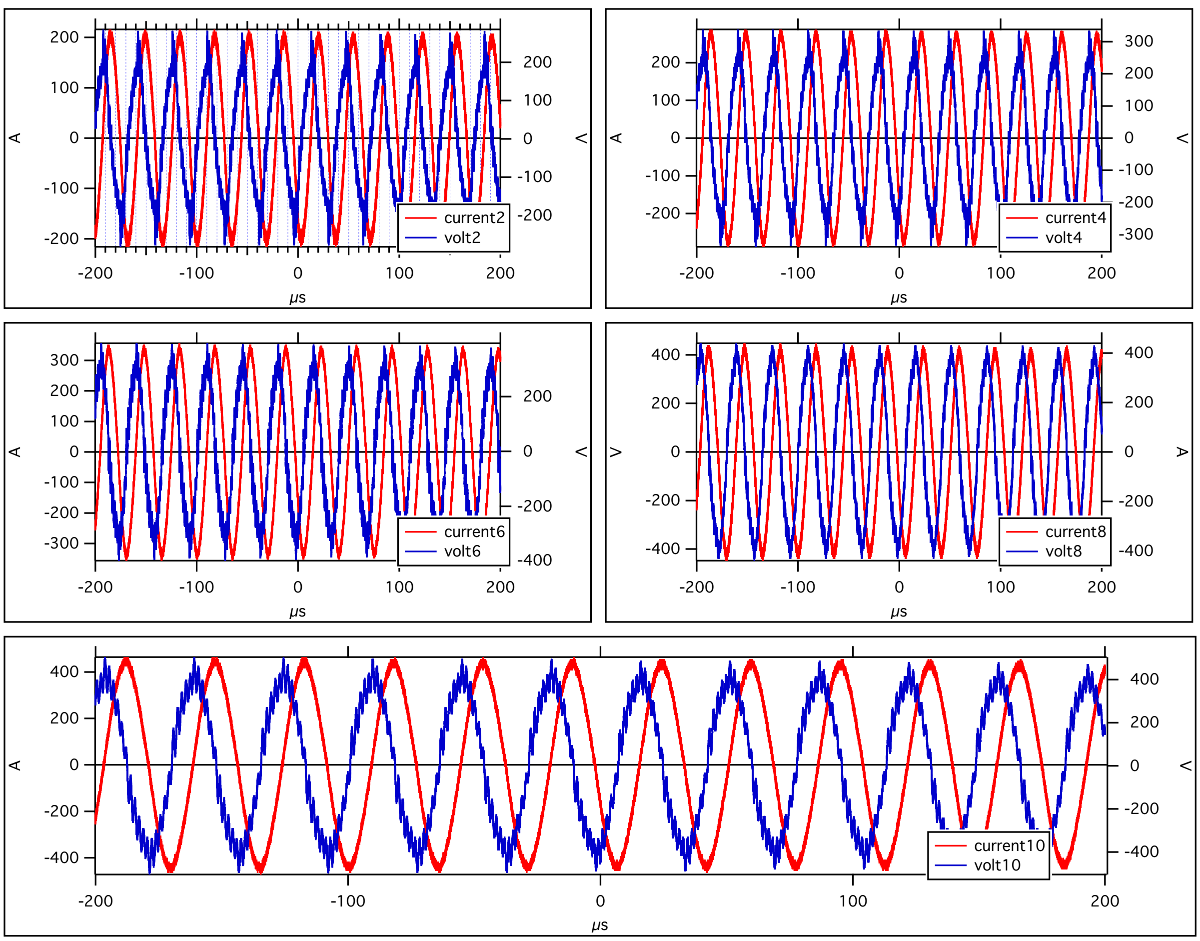

Figure 5: Display waveforms of all IV measurements at 23 kHz.