

Power Calibration is Getting Much Easier

Application Note

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Direct Digital Synthesis of the voltage and current waveforms used for watt-meter calibration has made the task of controlling the phase relationship between them much simpler. The techniques developed in the 5500A and 5520A Multi-Product Calibrators can be extended to improve uncertainties and to three phase systems. This application note outlines the evolution of this technology and explains how it can be extended to improve power calibration accuracy, even in three-phase applications.

The technology inside the 5500A and 5520A Multi-Product Calibrators makes it easier to calibrate power, even three-phase power.

In the 1970s and 1980s, calibration standards known as Multifunction Calibrators began to replace instruments that could provide calibrations for only one or two electrical quantities. These new instruments could provide, in a single enclosure, direct voltage, alternating voltage, resistance, direct current, and alternating current for the calibration of a wide range

of digital multimeters. In the 1990s, Multi-Product Calibrators were introduced with the goal of supporting the calibration needs of a wide range of *workload* including DMMs, thermocouple thermometers, RTD thermometers, capacitance meters, chart recorders, oscilloscopes, and wattmeters. Some of the features incorporated in these new calibrators make wattmeter calibration even easier and more accurate.

Traditional power calibration

Even though Multifunction Calibrators could source voltage or current, they were not capable of providing these basic power calibration signals simultaneously. Power calibrations have been performed using “golden standards,” other wattmeters used as transfer standards, power calibrators, expensive systems dedicated to power calibration, or phase locking multiple Multifunction Calibrators together. Figure 1 shows such a multifunction calibrator system for the calibration of single phase watt-meters. It consists of separate calibrators for voltage and current as well as an amplifier to provide higher currents to the UUT. A three phase system would take six calibrators and three amplifiers.

Power calibration using a multi-product calibrator

Figure 2 shows the same wattmeter calibration with a single Multi-Product Calibrator. It is able to perform this calibration by the ability to output voltage and current simultaneously and to control the phase relationship between them. In addition, the Multi-Product Calibrator can source up to 20 A without the need for an additional current amplifier.

The Fluke 5520A Multi-Product Calibrator allows locking the phase relationship precisely between multiple units allowing three phase power to be calibrated easily with three calibrators. Because the phase relationship between outputs can be controlled, the current outputs of multiple calibrators can be summed as well. This means that a three phase calibration system can be used to output current or single phase calibrations of up to 60 A. Figure 3 shows a simplified block

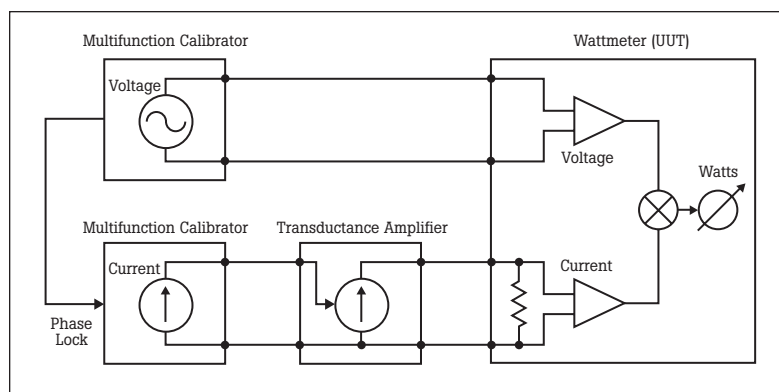


Figure 1: Multifunction Calibration of a Single Phase Wattmeter

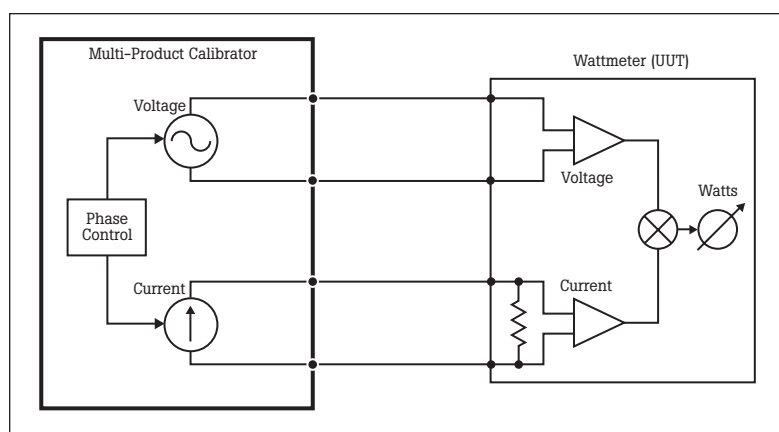


Figure 2. Multi-product calibration of a single phase wattmeter.

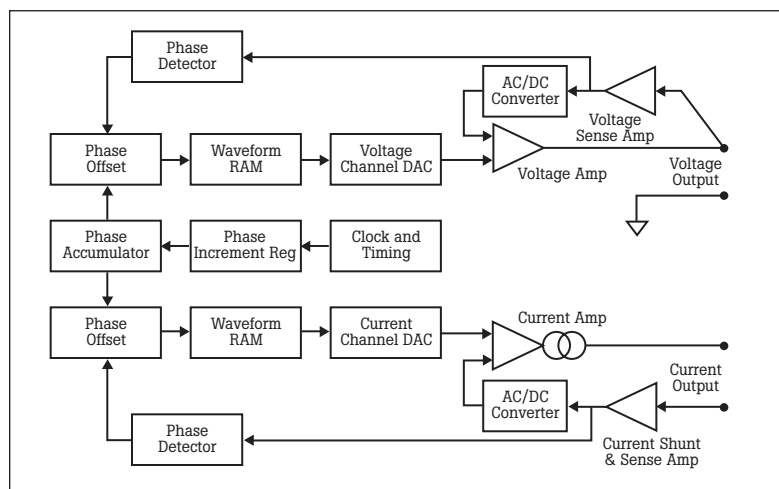


Figure 3. Multiproduct calibrator block diagram.

diagram of the 5520A Multi-Product Calibrator.

The Clock and Timing Circuit causes the Phase Accumulator to be incremented in regular intervals by the phase stored in the Phase Increment Register. The Waveform RAM

is addressed by this value offset by the value in the Phase Offset Register. Two Phase Offset registers are provided to allow each channel to be offset relative to a master “start-of-record” sync pulse. This sync pulse allows one

calibrator designated as the master to provide the clock and a sync pulse to other units so three phase calibrations can be performed with the ability to set the phase of each of the six outputs in any relationship to the others. Dual Phase Offset registers allows another important feature of the new calibrator. The phase of each channel is sensed at the output and the Phase Offset register adjusted to compensate for any phase shifts due to loading effects.

Power calibration presented unique design challenges. Some are described in this application note not only to show some of the design aspects of such a calibrator but also to indicate some of the hazards to the preservation of accurate signals external to the calibrator.

Uncertainty analysis

For a complex parameter such as power, the uncertainty analysis can be quite complex as well. A simplified analysis for the uncertainty of the power function is shown in this section.

$$\text{Eq. 1 } U_P = U_V \oplus U_I \oplus (U_\phi \bullet S_\phi^P)$$

Power is a function of the voltage, current, the phase relationship between them, and the sensitivity of power to the phase. The symbol, \oplus , indicates the combining of uncertainties. They can either be arithmetically added or a square root of the sum of the squares of the uncertainties may be used. It is appropriate to use the root-sum of squares when the uncertainty contributions are independent and random and to arithmetically add the uncertainties when they are correlated. In the detailed treatment of the uncertainties, both methods were used where appropriate. Because the calibrator can

operate over a wide range of voltages, currents, frequencies, and phase angles (power factors), crosstalk between the voltage and current is a factor that must be considered. The expression of uncertainty in Equation 1 is expanded in Equation 2 to show the contribution to uncertainty due to crosstalk.

Equation 2 tells us that the uncertainty in power is a function of the uncertainties in voltage, the influence of current upon the voltage, current, the influence of voltage upon current, phase, the influence of voltage on the phase, the influence of current on phase and the phase angle itself.

Voltage uncertainty

Voltage uncertainty was improved considerably in the new calibrator, but primarily for meter calibration. For power calibrations, it is always combined with other uncertainties which are larger and therefore is never the largest contributor to the overall uncertainty. The voltage is sensed at the output binding posts but some care must be still taken to ensure that the loading imposed on the voltage output is within the calibrator's specifications.

$$\text{Eq. 2 } U_P = U_V \oplus U_{I \rightarrow V} \oplus U_I \oplus U_{V \rightarrow I} \oplus [(U_\phi \oplus U_{V \rightarrow \phi} \oplus U_{I \rightarrow \phi}) \bullet S_\phi^P]$$

Voltage uncertainty due to current

Shifts in the output voltage can occur as a function of the current channel affecting calibrations at high currents with low voltages. Our tests indicated that these shifts could be fairly accurately modeled as a mutual inductance, M , between the current carrying leads and the voltage or voltage sensing leads. This coupling can occur in the calibrator, the unit under test, and the interconnections in either the high or low leads. A mutual inductance between the high current lead and the low of the voltage output is shown below in Figure 4. Since the mutual inductance internal to the instrument can be quantified and its effects are calculable, the degradation due to internal mutual inductance was reduced significantly. The voltage induced by the current, I , at frequency, f , is $V = 2\pi f M I$. However, this induced voltage leads the current waveform by approximately 90° in phase. At unity power factor, voltage and current in phase, it is also leads the voltage waveform by 90° resulting in little error. As the phase, ϕ , changes between the channels, the error increases proportional to $\sin \phi$. The error voltage, V_e , is that contribution of this interfering signal which is in phase with the voltage channel, $2\pi f M I \sin \phi$.

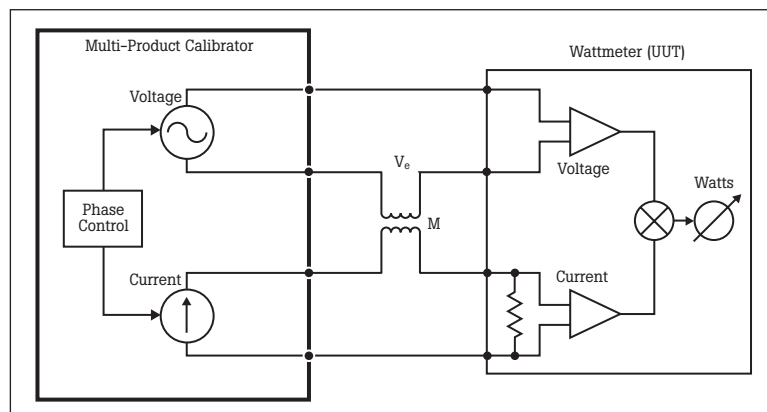


Figure 4. Coupling of Current into Voltage with a Mutual Inductance (M).

Current uncertainty

For lower frequencies, at unity power factor, the uncertainty of the current is the largest contributor to the power uncertainty. Therefore, considerable effort was made in the design to maintain current accuracies.

Current uncertainty due to voltage

Similar to the coupling of current into voltage, the voltage channel can be coupled into the current channel. In most cases, the coupling mechanism can be modeled as a stray capacitance. If the voltage and current channels were isolated, the capacitance would cause only a common mode signal to be coupled from the voltage channel to the current channel. However, so that the microprocessor can control both channels without having to design isolated digital control circuitry, it is required that the lows of the current and voltage channels be common to within a few tenths of a volt. This connection may be made in the calibrator, in the UUT, or external. Even if the channels were isolated, it is unlikely that the isolation to earth would be less than the tenths of a picofarad required to keep the errors manageable. Internal to the calibrator, this capacitance is calculable and stable and its effects can be taken into account arithmetically with the calibrator's microprocessor. Externally, when high voltages are used with relatively low currents, the high voltage lead should be shielded and not run too close to the current leads. The error current, I_e , lags the voltage channel in phase by 90° making the magnitude of the signal which actually interferes with the magnitude of the current channel, $2\pi fCV\sin\phi$.

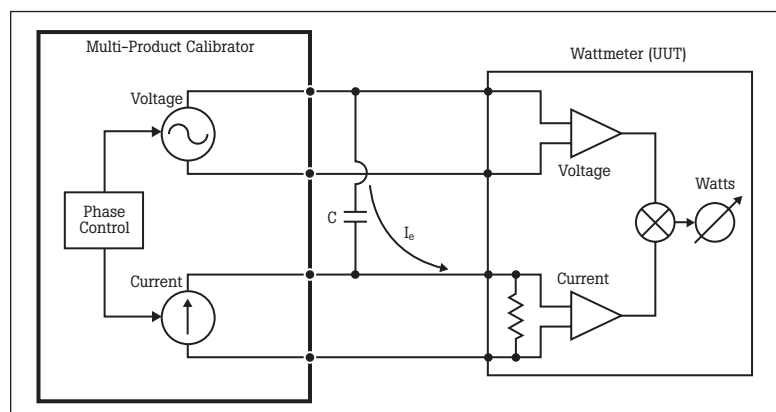


Figure 5. Coupling of Voltage into the Current Channel with Stray Capacitance (C).

General Power Formulas

Instantaneous Power: $p(t) = v(t) \cdot i(t)$

Average Power of a periodic waveform of period T: $P = \frac{1}{T} \int_0^T v(t) \cdot i(t) dt$

PowerFactor, PF = $\frac{\text{Average Power}}{V_{\text{rms}} I_{\text{rms}}} = \frac{\frac{1}{T} \int_0^T v(t) \cdot i(t) dt}{\frac{1}{T} \sqrt{\int_0^T v^2(t) dt} \cdot \frac{1}{T} \sqrt{\int_0^T i^2(t) dt}}$

Power Formulas for Sinusoidal Waveforms

$v(t) = V_p \cdot \sin(\omega t)$ and $i(t) = I_p \cdot \sin(\omega t)$

Where, V_p = Peak Voltage I_p = Peak Current
 $\omega = 2\pi f$ (f = frequency) t = time

Instantaneous Power: $p(t) = V_p \sin(\omega t) \cdot I_p \sin(\omega t + \phi) = \frac{V_p \cdot I_p}{2} [\cos\phi - \cos(2\omega t + U_\phi)]$

Where, ϕ = Phase relationship between $v(t)$ and $i(t)$

U_ϕ = Uncertainty of the phase relationship between $v(t)$ and $i(t)$

Average Power: $P = \frac{V_p \cdot I_p}{2} \int_0^T [\cos\phi - \cos(2\omega t + U_\phi)] dt = V_{\text{rms}} I_{\text{rms}} \cos\phi$

Where, $V_{\text{rms}} = \frac{V_p}{\sqrt{2}}$ and $I_{\text{rms}} = \frac{I_p}{\sqrt{2}}$

Power Factor, PF (Displacement Power Factor, DPF) = $\frac{V_{\text{rms}} I_{\text{rms}} \cos\phi}{V_{\text{rms}} I_{\text{rms}}} = \cos\phi$

Uncertainty in Power Due to the Uncertainty in Phase:

$U_p = 1 - \frac{V_{\text{rms}} I_{\text{rms}} \cos(\phi + U_\phi)}{V_{\text{rms}} I_{\text{rms}}} = 1 - \cos U_\phi + \sin U_\phi \tan\phi \approx \sin U_\phi \tan\phi$

Uncertainty times Power Factor: $U_p \cdot PF \approx \sin U_\phi \tan\phi \cos\phi$

Phase uncertainty

The uncertainty in power due to phase is a function of both the uncertainty of the phase and the phase itself. As shown in the formulas at left, which goes to infinity at 90° . That, of course, makes sense.

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