POWER CALIBRATION STANDARD BASED ON DIGITALLY SYNTHESIZED SINEWAVES

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Abstract

The unit of electric power at 60 Hz is often derived using impedance bridge techniques in which the alternating voltage is referred to the direct voltage standard through a thermal converter. An alternative calibration technique is described in which the ac to dc transfer is made through digital-to-analog converters (DACs) in the form of a dual-channel digital sinewave generator. The power is calculated from measurements of voltage, current, and phase angle, all of which rely on the accuracy of the digital generator and ultimately on the accuracy of the DACs. Measurement uncertainties of less than 100 ppm have been achieved.

Introduction

The electrical units of power and energy at line frequencies are established most accurately using thermo-electric techniques. The difference between the ac and dc response of a thermal voltage converter may be determined to an uncertainty of less than 5 ppm [1]. Using this relationship, current comparator bridges have been developed which are capable of measuring ac power, in terms of the basic units of resistance and dc voltage, with uncertainties of less than 30 ppm [2,3]. The ac to dc transfer is made at the test voltage (normally 120 volts) requiring a dc standard at that voltage. In addition, the transfer process may take several minutes due to long time constants of the thermal converters.

An alternative calibration technique (also a power bridge) which performs the ac to dc transfer at low voltage using a digital sinewave generator rather than a thermal converter is described. The generator relies upon a dc calibration of a high resolution digital-to-analog converter (DAC) which is used to synthesize a sinewave of known rms value. The relatively high test voltage and current are scaled by means of accurate transformers and shunts to low levels and compared to the synthesized signals, while an accurate phase relationship between voltage and current is established by the digital generator.

The excellent phase linearity between two digitally generated sinewaves has been demonstrated in the development of phase angle standards [4], power factor standards [5], and zero-power-factor wattmeter calibrations [6].

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Digital Generator

The digital generator, shown in figure 1, consists of a dual channel angle generator, a high-speed angle-to-sine converter, and two 16-bit digital-to-analog converters.

The outputs are staircase approximations of a sinewave (a zero-order-hold reconstruction) consisting of 4096 steps per period. At 60 Hz each step is approximately 4 μseconds wide. Low pass filters (LPF) reduce the total harmonic distortion of each output waveform to less than 50 ppm at power frequencies.

The DACs have a peak output swing of ±10 volts which results in a 7.07-volt (rms) sinewave. It has been shown that the rms value of a sinewave reconstructed with 16-bit resolution can be predicted to within 15 ppm [7], particularly at frequencies under 100 Hz. This figure does not include uncertainties in the dc reference (gain calibration) of the DAC; however, 10-volt dc standards with errors of less than 5 ppm are available.

Dynamic properties of the DAC and filter, which could cause significant errors in the average value of the waveform (i.e., "glitches" and overshoot), contribute negligible energy and thus do not seriously degrade the rms accuracy. These and other effects, such as amplifier slew limiting are further reduced by bandlimiting in the active LPF which converts the DAC output current to a voltage. Short-term amplitude stability of the generated sinewave was monitored by a thermal voltage converter and found to be better than 10 ppm.

The phase angle separating the two signals is changed by calculating a different series of data points for one of the channels. Phase angles between -360 and +360 degrees may be selected through the controlling microcomputer. Angular resolution is 1 part in 2^{18} or 0.0013 degrees

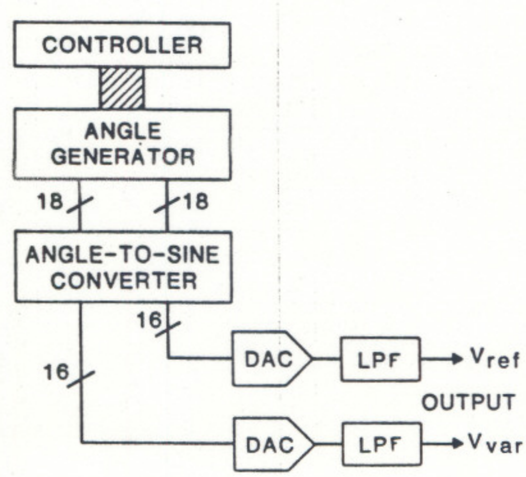

Fig. 1. Block diagram of the Digital Generator.

(24 μradians). Since the phase adjustment is digital, errors normally associated with analog circuits are greatly reduced. Short-term phase drift and nonlinearity are on the order of 15 μradians [5].

Calibration (Test) Circuit

The digital generator is the signal source for the power bridge shown in figure 2. Inductive voltage dividers T5 and T6 scale the signals applied to power amplifiers A1 and A2 which provide the test voltage (V) and test current (I) to the meter under test (MUT). T1 is a two-stage transformer which scales the test voltage of 120 V to 0.6 V with a ratio uncertainty of less than 2 ppm and a phase uncertainty of less than 2 μradians [8]. Resistor R1 is a four-terminal, 0.1-ohm ac shunt which converts the test current of 5 amperes to 0.5 Volts with a phase uncertainty of 1 μradian at power frequences [9]. The test current also flows in two-stage transformer T2 which scales the current to 50 mA developing a voltage of 0.5 volts across resistor R. The ratio uncertainty of this current-to-voltage conversion (including T2 and R) is estimated to be less than 12 ppm.

Three independent adjustments are required to balance the power bridge.

1. The voltage V is set with the switches (which select the signals applied to T3 and T7) in position a. Phase-variable voltage V_{var}, a 7.07-volt signal established by the digital generator, is scaled to 0.6 volts by inductive divider T3. A test voltage of 120 volts is obtained by adjusting T5 and the phase angle setting of the digital generator to produce a null at detector B.

2. The test current is set in a similar manner by scaling the generator signal to 0.5 volts with the switches in position b. It should be noted that this is a magnitude measurement which is insensitive to small phase errors in T2 and R.

3. The phase relationship between voltage and current is established by adjusting inductive divider T4 (magnitude adjustment) and the phase angle setting of the digital generator to produce a null at detector A. For this balance, detector B is disconnected from T1 by placing the switches in position b. The phase balance nominally occurs at 180° and the deviation from nominal is stored as a correction to be applied at other phase settings.

The power applied to the MUT is thus established by measuring voltage, current, and phase angle.

At balance the phantom power delivered to the MUT is given by

$$P = VI \cos\theta$$

$$= [V_{var}\ \rho_{var} N_1]\cdot[V_{ref}\ \rho_{ref}\ N_2/R] \cdot[\cos(\theta + \theta_c)]\ , \quad (1)$$

where V_{var} and V_{ref} are nominally 7.071068 V_{rms},

ρ_{var} is the inductive divider T3 setting in switch position a,

ρ_{ref} is the T3 setting in switch position b,

N_1 is the voltage ratio of transformer T1 (nominally 120:0.6)

N_2 is the current ratio of transformer T2 (nominally 5:0.05)

θ is the phase angle set by the digital generator, and

θ_c is the deviation from nominal obtained from balance 3 described above.

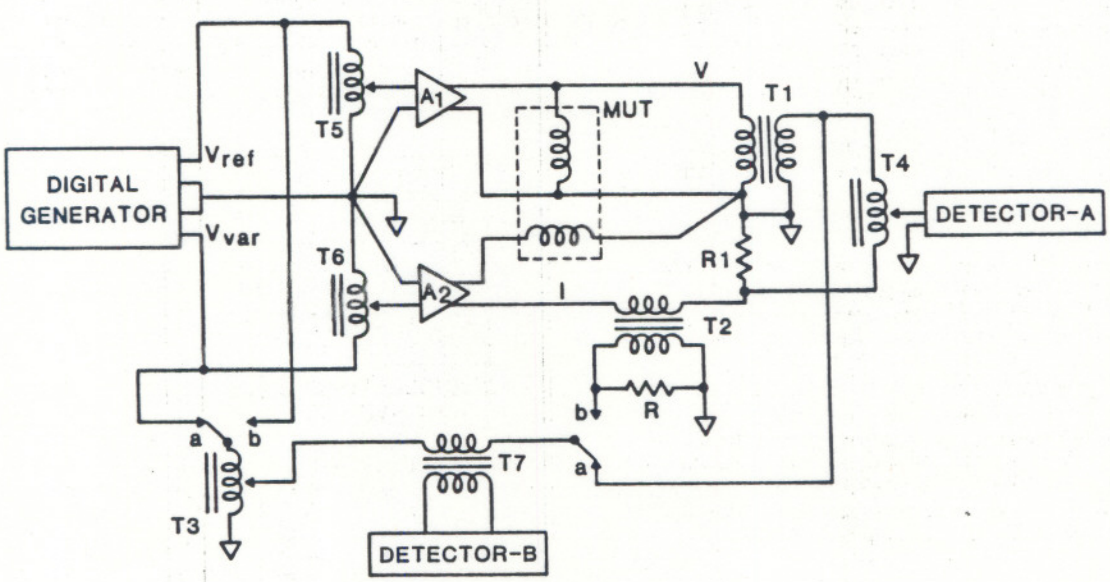

Fig. 2. Power bridge using the digital generator as a signal source.

The uncertainties associated with each quantity, and the root-sum-squares (rss) are given in Table 1. Several sources of error were compensated or found to produce immeasurable effects and are not included in the table. One such error source is asymmetrical capacitive coupling in T7 which produces different balance points depending upon how T7 is connected. The effect was minimized by isolating the windings on opposite sides of a toroidal core until an immeasurable change was observed by reversing the transformer inputs. An error in the phase balance due to the loading of T1 and R1 by T4 was measured by adding an impedance similar to T4 (typically 100 kilohms) across T4 and observing the new phase angle required to achieve a balance. While small magnitude changes were noted, the phase balance appeared unchanged to within the 5 µradians resolution of the measuring circuit.

Table 1

Parameter	Estimated Uncertainties Magnitude (ppm)	Estimated Uncertainties Phase (µrad)
V_{var}	20	
V_{ref}	20	
$\rho_{var} \times \rho_{ref}$	10	
N_1	2	2
N_2	2	
R	10	
R1		1
ρ_θ		5
Phase linearity		16
rss	$\alpha = 32$	$\beta = 17$

The error at a power factor of 1.0 is relatively insensitive to phase; thus the systematic uncertainty, at that point is simply α, the rss figure for the magnitude uncertainty. The uncertainty in θ_C is β, the combined rss phase uncertainty from T1, R1, and T4 (ρ_θ in the table) and the phase nonlinearity of the digital generator which is calibrated at 180° and used at other angles. The maximum systematic uncertainty (in ppm of apparent power, VI) at any phase angle θ, in radians, is given by

$$U_s = \frac{1}{VI}\left[VI(1+\alpha)\cos(\theta\pm\beta) - VI\cos\theta\right]$$
$$\approx \alpha\cos\theta \pm \beta\sin\theta \,. \qquad (2)$$

In addition to systematic uncertainties, a number of random errors degrade the bridge performance. The most significant of these include amplitude and phase instabilities in the power amplifiers and limited phase resolution in the digital generator (24 µradians).

Test Results

[illegible] selected test points. The wattmeter selected uses a thermal converter to compare the measured ac power to an internal dc reference with an uncertainty of less than 50 ppm [10]. Tests performed at 60 Hz were influenced by line frequency beats; therefore, 50 and 70 Hz data were included. All tests were performed at 120 volts and 5 amperes with the phase angle between the voltage and current ranging from -90 to +90 degrees. The errors in ppm are plotted versus phase angle in figures 3, 4, and 5.

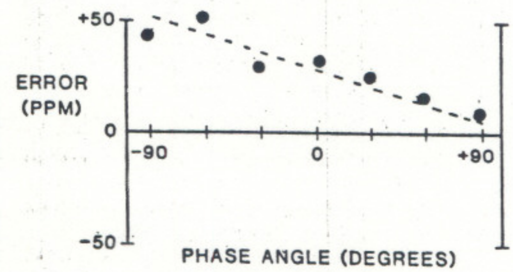

Fig. 3. Test results at 50 Hz. Standard deviation of the fit = 6 ppm.

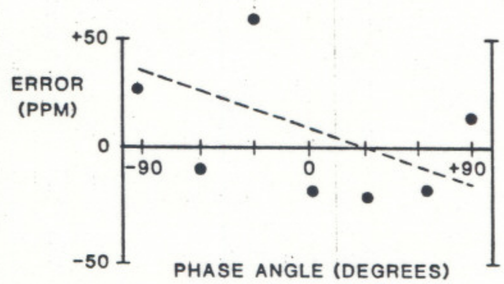

Fig. 4. Test results at 60 Hz. Standard deviation of the fit = 39 ppm.

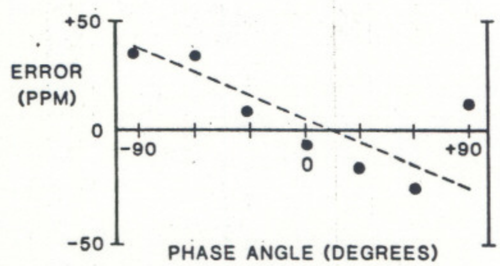

Fig. 5. Test results at 70 Hz. Standard deviation of the fit = 14 ppm.

A least-squares linear fit was made to each data set and the standard deviation of the residuals (difference between data and the values predicted by the fit) is given for each plot. An error margin of three standard deviations (SD) is used in estimating the total uncertainty (U_T) of each measurment

$$U_T = U_s + 3SD \,. \qquad (3)$$

Since U_S has a maximum value of 36 ppm, the total estimated uncertainty of measurements made by the bridge at 50 and 70 Hz is under 80 ppm. The 60 Hz uncertainties are larger due to beat-frequency instability. It can be seen from the error plots that the values fall well within 130 ppm (the combined uncertainties of power bridge and the wattmeter).

Other Approaches and Improvements

While the circuit shown in figure 2 is capable of power measurements over a wide range of voltages and currents, it is somewhat cumbersome, requiring three balances and two characterized ac resistors. A simplified circuit is shown in figure 6 which requires only two balances and one ac resistor. This circuit has the additional advantage that balances are made with signals of the same amplitude and phase; therefore, T4 does not load transformers T1, T2, or T3. Voltage-to-current ratios, however, are restricted to one value unless R is made variable. Limited measurements using this circuit have demonstrated an improvement in random error (over the results obtained with the circuit of figure 2).

Further improvements in the digital generator phase resolution and accuracy are possible using higher resolution DACs and sine look-up tables. Highly linear 18-bit DACs which can be updated every 10-20 μs are commercially available. At these speeds, a 60 Hz sinewave may be constructed using 1024 (2^{10}) steps. With a fast microcomputer to calculate and store a new series of sines, it appears possible to phase shift two digitally generated signals with a resolution approaching 1 μradian. Uncertainties of less than 10 ppm in the predicted rms value of the waveform appear to be feasible using 18-bit converters.

The beat-frequency problem encountered at 60 Hz can be eliminated by phase-locking the digital generator to the line. This is easily done by replacing the internal clock (approximately 250 kHz derived from a crystal source) with an external clock derived from line frequency.

Amplitude and phase instability in the power amplifiers are major sources of random error causing short term power fluctuations of 20 to 30 ppm. A recently developed transconductance current amplifier (to be described in a later paper) should improve measurement stability by a factor of two or three.

Conclusions

An accurate ac power measuring technique which refers to the dc volt through a digital-to-analog converter, rather than a thermal converter has been described. Determining the rms value of an unknown signal using a thermal converter requires approximately 5 mA from the signal source (to heat the thermocouple junction), and several minutes to perform the ac to dc transfer. On the other hand, two sinusoidal signals of the same frequency can be compared in a simple bridge much faster without loading either signal. In addition, since the measurement draws neglegible current, the signals can be accurately scaled to a convenient low level with passive transformers, and then compared with a digitally synthesized signal of known rms value. Estimating the rms value of the synthesized signal based upon a dc calibration of the DAC is not yet as accurate as the conventional thermal measurements; however, it is extremely useful as an independent approach and has the potential of achieving uncertainties on the order of 5-10 ppm.

The described power bridge differs in other ways from existing the current comparator bridges [2,3]. Unlike the current comparator systems which require low-loss capacitors to measure power factors other than unity, this approach relies upon the excellent phase linearity, made possible by the digital generator, to establish any phase angle. Once the initial balances have been performed, measurements at different power factors are made simply by changing the phase setting of the digital generator, and no rebalancing is required.

Results of a wattmeter calibration demonstrated standard deviations of about 20 ppm. Combined with systematic errors of about 40 ppm, the total uncertainty of measurements made by the bridge are on the order of 100 ppm. By incorporating some of the described improvements, total uncertainties of 30 ppm should be possible, making this approach a valuable independent cross check on the existing thermal power calibration systems.

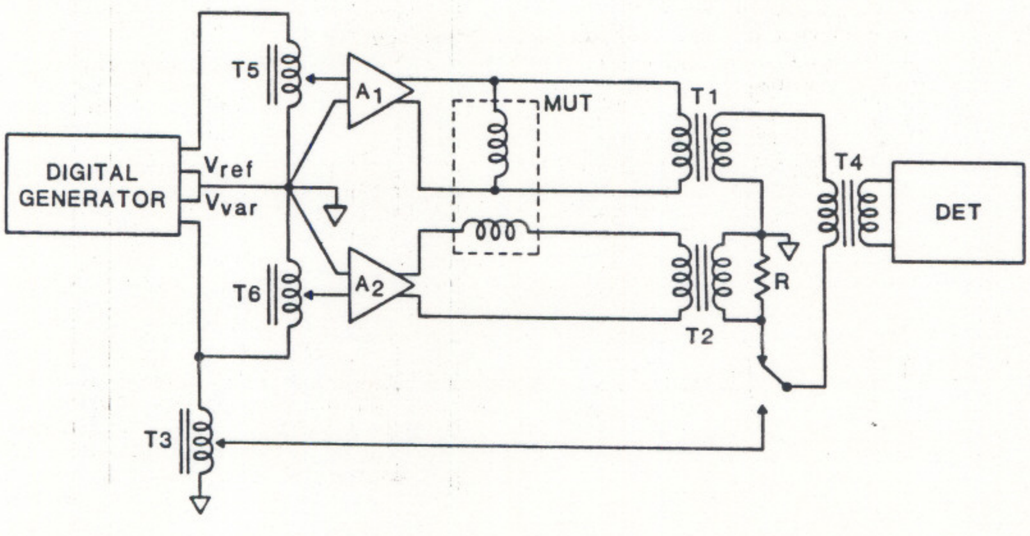

Fig. 6. Simplified bridge requiring only two balances.

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