Wideband Wattmeter Based on RMS Voltage Measurements

Bryan Cristopher Waltrip, Member, IEEE, and Nile M. Oldham, Senior Member, IEEE

Abstract—A wideband wattmeter for measuring active power over a frequency range of dc to 500 kHz is described. The wattmeter is based on the three-voltmeter method in which three rms voltage measurements are used to calculate power. The wattmeter active power uncertainty is estimated to be within 0.03% from dc to 20 kHz and within 1.5% to 500 kHz.

Index Terms—binary inductive voltage divider, buffer amplifier, digital voltmeter (DVM), law of cosines, power, three-voltmeter method, wattmeter.

I. INTRODUCTION

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HE three-voltmeter method (TVM) for measuring power was described by Ayrton nearly 100 years ago. After remaining dormant for a number of years, the three-voltmeter method was revived with the advent of the operational amplifier. More recently, precision wideband digital voltmeters have made it a viable approach for measuring power at any power factor from dc to 500 kHz. Various implementations of the technique have been described in the literature [1], [2]. Basically, the applied power is derived from a set of three rms voltage measurements using the law of cosines. This paper describes a new wattmeter that is being developed to provide wideband calibration support for a new class of commercial power analyzers that utilize waveform sampling in the dc to 400 kHz frequency range.

II. TVM Wattmeter Design

A wideband wattmeter has been designed and constructed that is based on the TVM principle. It employs a commercial digital voltmeter (DVM), a four-terminal resistor, resistive and inductive voltage dividers, an isolation transformer, and associated control circuitry. This TVM wattmeter was designed to be used with a source of synthetic power to test wattmeters over a wide range of power, power factor, and frequency. A simplified circuit diagram of the test system for testing wattmeters above 50 Hz is shown in Fig. 1. The synthesized voltage is applied to the voltage terminals of the wattmeter under test (MUT) and to inductive voltage divider, which is used in conjunction with the buffer amplifier to produce a scaled version of the applied voltage. The current, , is applied to the four-terminal resistor, , in series with the current terminals of the MUT. The voltage developed across is applied to buffer amplifier, , and then converted to a ground-referenced voltage, , using the two-stage voltage transformer, , and buffer amplifier, . The difference voltage, , is converted to a ground-referenced voltage, , using a center-tapped inductive voltage divider, , and buffer amplifier, , thereby avoiding the need for any active circuitry to perform the summing function. A high-precision, wideband DVM is used to measure the three ground-referenced voltages, , , and . These voltages are related to the phase angle between and by the Law of Cosines

\[ V_B = V_1^2 + V_2^2 - 2V_1V_2\cos\theta \]  

which may be expressed as

\[ V_1V_2\cos\theta = (V_1^2 + V_2^2 - V_B^2)/2. \]  

The magnitude of the difference voltage, , can be described in terms of the three measured voltages and the ratio of the voltage transformer by

\[ V_D = [2(V_1^2 + V_2^2 - V_B^2)]^{1/2}. \]  

The power applied to the MUT is given by

\[ P = VI\cos\theta = (r_1r_2V_1V_2\cos\theta)/R \]  

where is the step-down ratio of and is the step-up ratio of .

A. Voltage Dividers

The voltage, , is reduced from 120 V to approximately 0.5 V using inductive voltage divider [3]. For test signals between dc and 50 Hz, this divider is replaced by a fixed ratio (240:1) resistive divider.

B. Current to Voltage Converter

The current, , is converted from 5 A to approximately 0.5 V using the 0.1 Ω, four-terminal resistor [4]. To minimize common mode errors, the voltage developed across is isolated and converted to a ground-referenced signal using a 1:1 wideband two-stage voltage transformer, . To minimize the loading effect of , the signal is buffered using amplifier, , for test signals between dc and 50 Hz, the transformer is replaced by a unity-gain differential amplifier.

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C. Buffer Amplifiers

Perhaps the most difficult challenge in constructing a wideband wattmeter based on the three-voltmeter method is that of minimizing the complex loading imposed by $T_1$, $T_2$, and $T_3$. Loading is minimized using special composite, noninverting buffer amplifiers $A_1$, $A_2$, $A_3$, and $A_4$ [5]. A simplified diagram of the buffer amplifier is shown in Fig. 2. Its operation is analogous to a two-stage voltage transformer in that the first stage, $A$, drives the common of the second stage, $B$, to the signal voltage (to within the tolerance imposed by the loop gain of $A$). The second stage uses its loop gain to correct only the small difference voltage. It has been shown that the gain and phase errors of this buffer amplifier are less than five parts in $10^6$ in the 50 Hz to 1 kHz range [6].

D. Output Stage

The heart of the TVM wattmeter is the output stage where voltages $V_1$ and $V_2$ (proportional to the voltage and current) and $V_3$ (proportional to the difference voltage, $V_D$) are measured using a commercial DVM and processed to compute the $V_1V_2\cos\theta$ term in (1). A direct measurement of $V_3$ would be susceptible to common mode errors in the voltmeter, so $V_1$ and $V_2$ are applied to the 2:1 inductive voltage divider, $T_3$, to produce a ground referenced voltage, $V_D$, which is used to compute $V_D$. For test signals between dc and 50 Hz, the inductive divider is replaced with a 2:1 resistive voltage divider.

III. Test Results

The output stage of the TVM wattmeter was tested as a voltage multiplier by applying low-level voltage signals (approximately 0.5 V) to the inputs of $A_1$ and $A_3$, with $T_1$ and $R$ disconnected. To test the gain errors, a single 1 V signal was connected to both $A_1$ and $A_3$. The output voltages, $V_1$ and $V_2$, were measured using the DVM. Measurements were made between 100 Hz and 500 kHz. The difference between the computed power and the input voltage squared represents the gain error. To test the phase errors of the output stage, a phase standard was used to generate two, phase-adjustable, 0.5 V signals that were applied to $A_1$ and $A_3$. The phase angle between these signals was set to $90^\circ$, and measurements were made between 100 Hz and 100 kHz. The phase angle was then computed based on measurements of $V_1$, $V_2$, and $V_3$ using (2) and (3). The difference between the computed phase angle and that set using the phase standard represents the phase error. In the 100 Hz to 100 kHz range, the phase angles between the test signals were verified using a sampling phase meter with a phase measurement uncertainty of $<0.002^\circ$ [7]. Between
TABLE I
Estimated 1-Sigma Uncertainties of the TVM Wattmeter Components

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>$T_i$ (%)</th>
<th>$R$ (%)</th>
<th>$T_i$ (%)</th>
<th>$A_i - A_j$ (%)</th>
<th>$T_i$ (%)</th>
<th>DVM (%)</th>
<th>1-sigma Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.0003</td>
<td>0.0005</td>
<td>0.0005</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.001</td>
<td>0.0016</td>
</tr>
<tr>
<td>1</td>
<td>0.0009</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0006</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>10</td>
<td>0.002</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.001</td>
<td>0.0036</td>
</tr>
<tr>
<td>100</td>
<td>0.004</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.002</td>
<td>0.07</td>
<td>0.051</td>
</tr>
<tr>
<td>1000</td>
<td>0.02</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.02</td>
<td>0.1</td>
<td>0.497</td>
</tr>
</tbody>
</table>

While all of the TVM wattmeter components operate to 500 kHz, the version described in this paper has been optimized for the audio frequency range. It is evident from the performance evaluation of the multiplier circuit that a second type of buffer amplifier will be needed above approximately 20 kHz. It is estimated that a simple, one-stage buffer design will reduce the uncertainty projections above 20 kHz shown in Fig. 4.

IV. CONCLUSION
Standards to support precision power measurements presently are limited to the audio frequency range [6]. The TVM wattmeter described here is being developed to support the calibration of commercial power analyzers capable of measuring power components out to 400 kHz where no standards presently exist. In the dc to 20 kHz range, the TVM wattmeter uncertainty (0.003% to 0.03%) is comparable to the more complex current comparator bridge which presently serves as the audio frequency standard for power and energy.

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REFERENCES

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Since then he has employed as a Physicist (and later as an Electronics Engineer) in the Electricity Division at the National Institute of Standards and Technology, Gaithersburg, MD. His recent work at NIST includes the development of electrical standards of voltage, current, phase angle, power and energy using digital synthesis techniques. In related areas, he has developed electronic methods for improving optical interferometry for several nanometer-scale projects and has served as a consultant on two space shuttle projects.