Circuit to cancel ac displacement current to reveal dissipative and nonlinear conduction phenomena

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Conduction and dissipative phenomena which result in a small current compared to a displacement current are important in many contexts but are very difficult to measure as the displacement current may be a million times larger than the resistive and harmonic currents of interest. In principle, a dual phase lock-in amplifier can measure the average value of the rectified fundamental resistive current wave form; however, the accuracy of the phase reference and phase stability of the lock-in would have to be much greater than is practical. Further, such a measurement does not reveal the actual wave form or allow the measurement of harmonic current components which indicate nonlinear phenomena and may be of greater interest or of larger magnitude than the fundamental. The present circuit employs a dual phase lock-in amplifier in a feedback configuration which actively cancels the in-phase component of the current wave form to reveal the remaining current wave form components as well as provide a measure of the fundamental quadrature component via the lock-in. The active nature of the feedback assures long-term cancellation of the displacement current so that the nondisplacement current wave form can be monitored over time during evolution of the system as a result of aging, electrochemistry, etc.
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I. INTRODUCTION

In many ac electrical contexts, displacement current, 90° out of phase with the applied voltage, is many orders of magnitude greater than the in-phase or ''resistive current.'' As is well know, the in-phase current indicates dissipation within the electrical circuit from conduction, dipolar dissipation, etc. Further, nonlinear phenomena, such as electrochemical reactions, saturation effects, etc., can contribute small harmonic currents, the phase and magnitude of which can reveal information about the nonlinear phenomena.

In principle, a dual phase lock-in can measure the average value of the rectified in-phase signal. However, if the displacement current is 100 000 times larger than the resistive current, the phase reference and lock-in phase stability would have to be good to about 10^{-6} rad for a reasonably accurate measurement. This might be possible over short times in a laboratory environment; however, long-term stability during monitoring is unlikely. As well, such a measurement does not reveal the nondisplacement current wave form or facilitate the measurement of harmonics and the phase thereof.

We therefore describe circuitry which can be employed in conjunction with a dual phase lock-in to provide active, feedback-based cancellation of the displacement current so that the nondisplacement current wave form is revealed and so that the lock-in can provide an accurate measure of the average value of the in-phase current wave form. We employ such circuitry for measuring the dissipation and nonlinear phenomena which occur during electrochemical reactions in polymer-based systems, although such circuitry is useful in a wide range of applications including electrorheology, dielectric measurements, etc.[1–6]

II. DESIGN APPROACH

The approach is dictated by the large assumed difference between the capacitive current and the resistive current. The standard approach to such measurements is a passive bridge circuit in which the large signal is nulled to reveal the small signal of interest. We are employing a similar approach, but with active feedback to maintain the balance as the nature of the sample changes over time during measurement. A block diagram of the measurement system is shown in Fig. 1. The sample current is normally taken from the ground connection, while a reference capacitive current is generated by a near-perfect capacitor (vacuum, gas, polystyrene, etc., depending on the desired level of perfection). A phase shift circuit (RC divider) is provided in the reference arm to permit exact cancellation during setup at the beginning of the experiment. The output of the phase shift circuit is used as the reference signal to the lock-in. This signal also passes through a variable gain element, which consists of a resistive

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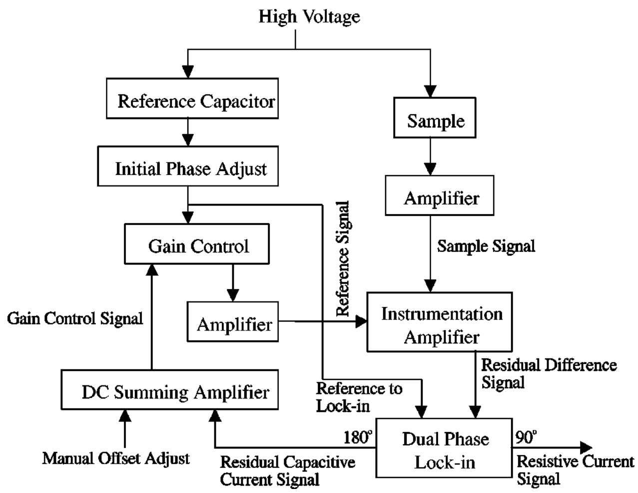

FIG. 1. Block diagram of electronics for cancellation of capacitive current.

divider with a photoresistor in one arm, and is applied to one input of an instrumentation amplifier, with the sample signal on the other input. The output of the instrumentation amplifier is fed to the input of a dual phase lock-in amplifier, the in-phase output of which (a measure of the displacement current) controls the attenuation of the variable voltage divider to provide negative feedback such that the circuit minimizes the in-phase output signal from the lock-in and thereby cancels the displacement current induced signal. A manual offset adjustment is provided so that the variable resistive divider can be set to approximately the correct quiescent point so that the feedback makes only corrections to this value. In this way, the capacitive signal can be canceled to the noise level of the lock-in. With the capacitive signal canceled, the output of the instrumentation amplifier represents the nondisplacement current portion of the ground current, including the ''resistive'' current at the fundamental and any harmonics caused by nonlinear phenomena.

The schematic of the system is shown in Fig. 2. The circuit combines a self-balancing electronic ''bridge'' to null most of the capacitive current followed by synchronous rectifiers to separate the resistive current from any residual capacitive current. The synchronous rectifiers in the dual phase lock-in amplifier also provide the feedback signal which controls the gain of the analog optoisolator (VTL5C3) in the reference signal circuit. The feedback nulls the capacitive signal so that the lock-in amplifier can detect the resistive signal without excessive interference.

III. CIRCUIT DESCRIPTION

A. High voltage

In our application, the high voltage ac is generated by a commercial audio amplifier driving an electrostatic speaker step-up transformer. The ac high voltage (1 kHz, 2.5 kV) is applied to the sample, which generates relatively large capacitive current and a much smaller resistive current. The high voltage is also applied to a resistive divider, the output of which is buffered to provide a reference voltage applied to a reference (polystyrene) capacitor which generates a nearly pure capacitive current. Both channels are protected by spark gaps to ground. The polystyrene capacitors have dissipation factors in the range of 5×10^{-5} so that they contribute appreciable resistive current. However, we normally null the reference and measurement arms at the beginning of an experiment so that we can see the change in resistive current over time.

B. Current to voltage conversion

The capacitive and the resistive currents from the sample are converted to voltages by AD549 operational amplifiers which have an input bias current of about 50 fA and are operated as integrating current to voltage converters. The feedback capacitors are polystyrene and must be selected to

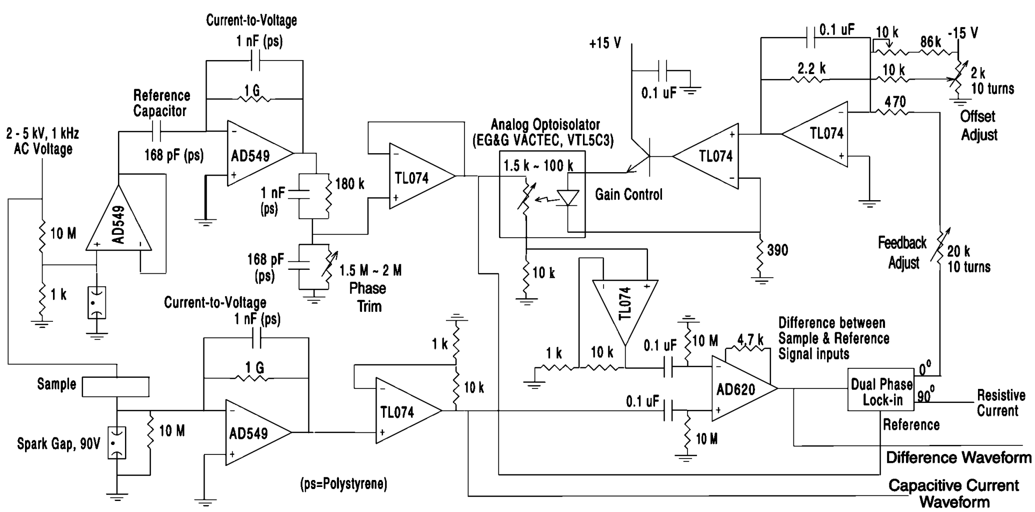

FIG. 2. Schematic for measuring ac resistive and dc ground current from a needle water tree sample without the use of a transformer. The instrumentation amplifier and feedback from the lock-in amplifier are used to cancel most of the capacitive current from the sample, leaving the resistive ac current and the dc current along with some residual capacitive current. The synchronous rectifiers (dual phase lock-in amplifier) are used to create a dc feedback signal proportional to the error in the ac compensation (cancellation) current and to create a voltage signal proportional to the ac resistive current. Much greater protection of the sample input to the AD549 can achieved through replacing the spark gap with a pair of hot carrier diodes; however, this will typically increase the input root-mean-sqare (rms) current noise by at least 3 dB with a disproportionate increase at very low frequencies (probably $1/f$ noise).

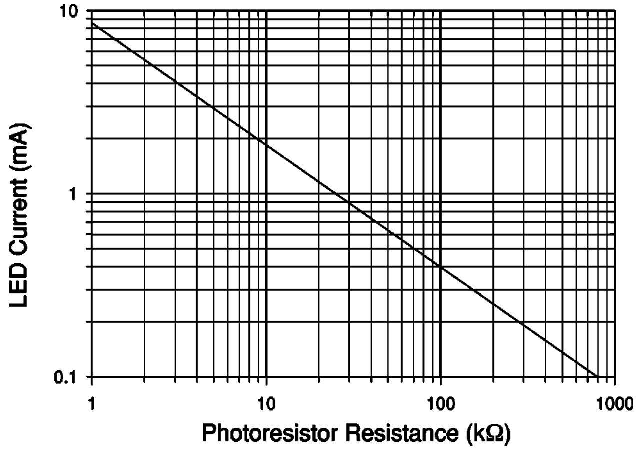

FIG. 3. Resistance vs LED current for optoisolator.

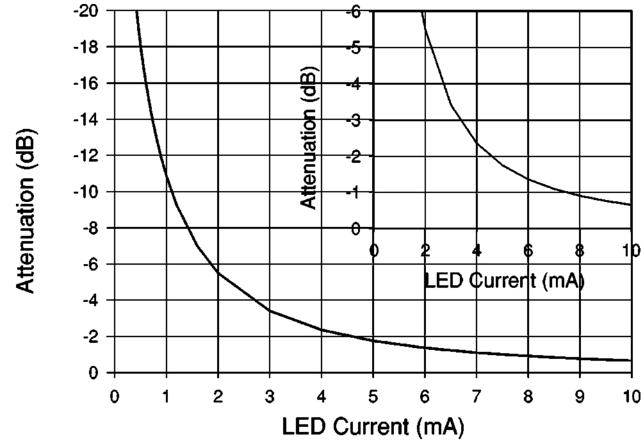

FIG. 4. Variable voltage divider attenuation as a function of LED current. The inset shows detail in the most important region around 6 dB attenuation.

provide appropriate signal levels at the AD549 output. Resistors are placed across the feedback capacitor to provide dc stability. Ideally, the RC time constant of the RC feedback pair in the integrating current to voltage converter of each channel (signal and reference) should be the same to minimize differential phase shifts.

C. Phase trim

The displacement current signal from the reference channel passes through a phase trim circuit consisting of a compensated RC divider with one variable resistor. The phase of the reference channel signal is normally trimmed to match the phase of the sample signal at the beginning of the experiment, as determined by the nulling of the resistive current signal so that the only remaining signal results from harmonics. The buffered output of the phase shift circuit also provides the reference signal for the lock-in amplifier.

D. Variable gain element and feedback

An optoisolator [VTL5C3 light emitting diode (LED) photoresistor pair] is used to change the attenuation of a resistive divider which is used to vary the amplitude of the reference channel signal. The current through the LED is controlled by a feedback signal from the in-phase (''*X*'') output of the dual phase lock-in amplifier to null the capacitive signal at the output of the AD620 instrumentation amplifier. For the circuit configuration shown, the lock-in reference phase must be set to 180° to achieve negative feedback. The output of the AD620 instrumentation amplifier goes to the signal input of the dual phase lock-in amplifier where the two synchronous rectifiers within the lock-in provide dc output voltages which are proportional to the in-phase and out of phase (relative to the lock-in reference channel input) input signal amplitude. The time constant employed in the lock-in is 3–30 s in order to provide stability in the high gain feedback loop. Since the reference signal is purely capacitive, the in-phase (0°) signal out of the lock-in is proportional to the capacitive signal out of the AD620 which is determined by the difference between the capacitive signal from the reference and signal channels. If we take this output, amplify it and apply it to the LED in the variable voltage divider, this feedback circuit will nearly null (depending on the feedback loop gain) the capacitive signal at the output of the AD620 and leave a nearly pure resistive signal at the input of the lock-in amplifier. This allows the lock-in to measure the resistive signal without being overloaded by a capacitive signal which is much greater than the resistive signal. The output of the instrumentation amplifier contains all signal components other than that caused by the displacement current so that the nondisplacement current wave form can be observed.

Figure 3 shows the photoresistor resistance as a function of the LED current, while Fig. 4 shows the resulting division ratio of the voltage divider which incorporates the photoresistor. However, the photoresistor has a capacitance of about 2.5 pF in parallel with its resistance. This results in a phase shift which increases with photoresistor resistance and is shown for a frequency of 1.0 kHz in Fig. 5. As a result, the maximum value of photoresistor should be limited. This can be achieved by setting gains in the circuit so that the variable attenuator which incorporates the photoresistor operates at as low a division ratio (as little attenuation) as possible. We

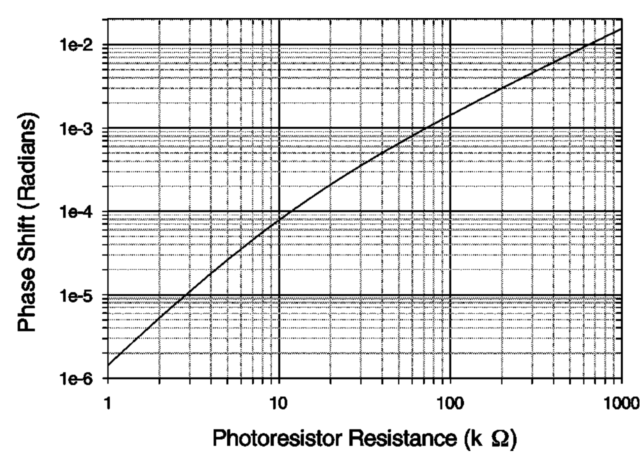

FIG. 5. Phase shift at 1.0 kHz vs photoresistor resistance which results from the 2.5 pF capacitance of the photoresistor. As a result, the maximum photoresistor resistance should be limited to about 100 kΩ, which results in a maximum attenuation of about 20 dB. The minimum attenuation is limited by the minimum resistor value of about 1 kΩ, which results in about 1 dB of attenuation.

also suggest including a potentiometer in the feedback circuit to the LED which provides a bias current so that the photoresistor resistance cannot go above about 100 kΩ (for which the phase shift is about 1.4×10^{-3} rad or 0.08°), unless, of course, the lock-in amplifier provides the necessary feedback. However, this condition would be immediately obvious to the operator, as the Offset Adjust could not be used to zero the feedback from the lock-in and achieve zero displacement current signal in the output of the AD620. Normally, the capacitance changes little during application of the circuit. However, if the capacitance changes a great deal, one must be aware of the error caused by the phase shift in the photoresistor divider.

From Fig. 4, we see that the ''gain'' of the feedback circuit is a strong function of the division ratio, especially for small division ratios. Thus, the gain of the feedback must be adjusted to accommodate changes in the divider gain as a function of its operating point. This is normally accomplished by increasing the feedback loop gain as much as possible without the risk of oscillation. The feedback loop gain can be adjusted by changing the setting of the 20 kΩ potentiometer and by changing the input sensitivity of the lock-in amplifier. Usually the X and Y outputs of a dual phase lock-in are something like 0–10 V in proportion to the full scale reading of the front panel meters. Thus, the loop gain increases with increasing sensitivity setting of the lock-in amplifier.

When the loop gain is set comfortably below oscillation with a 10 s time constant setting on the lock-in amplifier, the error of the residual reading of the in-phase output of the lock-in is fluctuating in the noise, the residual signal at the output of the instrumentation amplifier is clearly in quadrature with the lock-in reference signal, and this situation persists over long periods of time. Any change in the in-phase signal over time can be nulled at will by adjusting the 2 kΩ bias potentiometer.

E. Circuit adjustments

Three adjustments are provided in the circuit. The 10 turn, 20 kΩ potentiometer adjusts the feedback gain, which is also affected by gain settings in the lock-in amplifier. The gain should be maximized subject to avoiding oscillation of the circuit which will result from too large a gain. The 2 kΩ, 10 turn potentiometer adjusts an offset to the variable gain element. This should be adjusted to null the in-phase (capacitive) signal. Obviously, feedback is achieved only by amplifying an error. Thus, feedback can reduce error but never eliminate it. However, error can be reduced greatly by providing an offset adjustment so that the average error can be nulled manually using the offset adjustment, and the feedback only corrects the error from the average. This adjustment can be employed to null the in-phase signal so that the output of the AD620 represents the waveform of the out-of-phase (resistive) signal. As discussed above, a 10 kΩ internal adjustment is provided to limit the maximum resistance of the photoresistor to about 100 kΩ by setting a permanent bias on the LED current.

The only other adjustment is the phase adjustment prior to starting an experiment, which is necessary to match the phase of the reference and signal channels. This adjustment sometimes requires changing capacitors in the phase shift circuit, which are shown in Fig. 2 as 1 nF and 168 pF. Obviously, the gain of various stages may have to be adjusted to match the nature of the input signals, and should be set to minimize the division ratio of the variable resistive divider.

F. Output signals

Three signal outputs are provided. The signal from the sample channel is provided. In our circuit, this is rectified and filtered with a 0.1 s time constant to provide a signal which is proportional to the capacitive current. Technically, this signal includes the resistive current as well; however, the resistive current is normally much smaller than the capacitive current and can be ignored in comparison. The difference signal from the instrumentation amplifier (AD620) is provided to observe the nondisplacement current wave form. This signal accurately reflects the resistive current wave form if the offset is adjusted as discussed above to null the capacitive (in phase) signal as indicated on the dual phase lock-in. In our circuit, this signal is also rectified and filtered with a 0.1 s time constant to provide a signal which can be applied to a chart recorder to indicate the magnitude of the nondisplacement current as a function of time during an experiment. This signal differs from the quadrature output of the lock-in in two respects, viz., (i) the lock-in is often operated with a 10 or 30 s time constant to provide stability in the high gain feedback loop and (ii) the quadrature output of the lock-in is a measure of only the fundamental component of the nondisplacement current signal whereas this output is proportional to the average magnitude of the quadrature component of the fundamental and all harmonics.

G. Analysis and performance

The gain of the lock-in from the input to the feedback output is generally about 1000. The gain of the instrumentation amplifier is 10. We base our analysis of the feedback loop gain on the assumption that we have 2 V at the input to the variable ratio voltage divider which is operating at a division ratio of 0.5 (−6 dB), that the circuit has been nulled using the 2 kΩ offset adjust potentiometer, and that the 20 kΩ feedback adjust potentiometer is set to provide a circuit feedback gain of unity for the feedback signal from the lock-in.

From this initial state, if we had 1 mV error at the output of the instrumentation amplifier (caused by a 0.1 mV error in matching of the reference and signal inputs to the instrumentation amplifier), this would cause roughly a 1 V feedback output from the lock-in. This 1 V feedback signal (2.5 mA change in current through the LED) will cause a change of over 3 dB in the divider output or about 300 mV which is 3000 times greater than the required correction. Thus, if we use the 2 kΩ bias potentiometer to null the circuit, we expect the error caused by any subsequent drift to be reduced by a factor of roughly 3000 by the loop gain. In practice, the circuit holds the in-phase signal to within the noise of the lock-in for hours at a time. Long term drift caused by un-

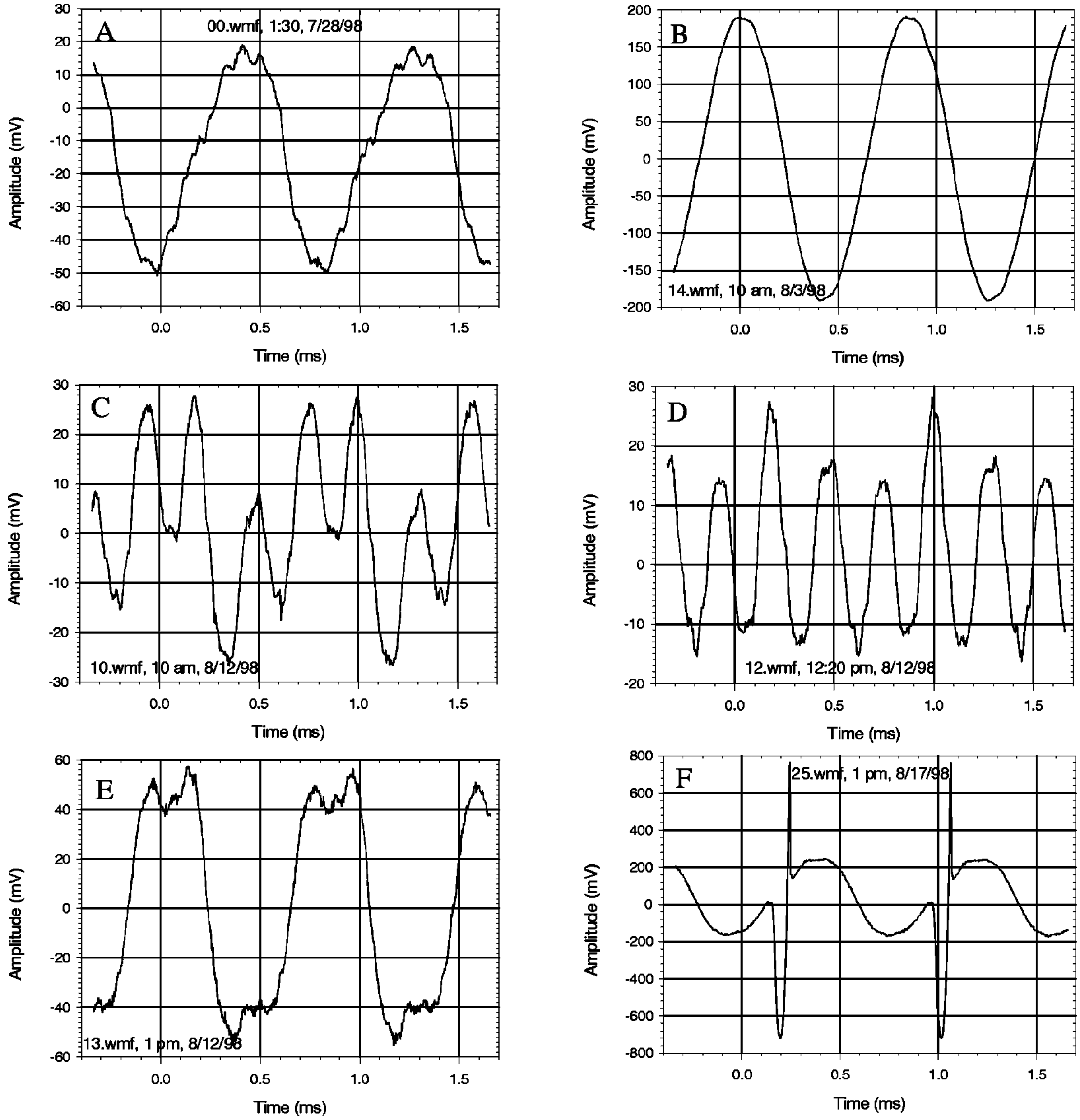

FIG. 6. Examples of the measured nondisplacement current during electro-oxidation of a polymer exposed to moisture and a large electric field.

compensated changes in signal capacitance can be nulled periodically by adjusting the 2 kΩ potentiometer to null the in-phase reading from the lock-in.

Figure 6 shows an interesting progression of nondisplacement current signals measured during electro-oxidation of a polymer sample exposed to moisture and a high electric field. Note that the polarity of the resistive voltage is inverted between Figs. 6(a) and 6(b), which means that in one case, the system is dissipating energy and in the other case, it is generating energy, which is a distinct possibility during an oxidative electrochemical reaction. Figure 6(c) has a large third harmonic component mixed with the resistive fundamental signal while by Fig. 6(d), the signal is almost entirely third harmonic, evidently caused by nonlinearity in the electrochemical reaction. The third harmonic signal has subsided by Fig. 6(e). Figure 6(f) shows a highly nonlinear condition. Note that the phase of the fundamental has again inverted, probably because the sample is very near failure and resistive conduction current is passing through the sample.

H. Stability

The stability of the circuit was checked with an instrumentation amplifier gain of 50 (as opposed to the gain of 10 employed during experimental measurements). During this test, the input currents to the reference and signal channels were provided by identical polystyrene capacitors. Table I shows the drift in the lock-in output recorded as a function of time over a period of roughly 20 h. Of course, the in-phase signal is being held to near zero by the feedback and drifts relatively little. The quadrature signal represents the drift in the circuit and can be expressed as an equivalent phase shift between the two signal inputs. The mean of the equivalent phase shift is -0.06 μrad, while the 99% confidence interval

TABLE I. System stability under static conditions.

Hours	In-phase output (mV)	Quadrature output (mV)	Equivalent phase shift (μrad)
0	-0.007	$+0.377$	1.66
1.5	-0.001	-1.750	-7.70
5.5	-0.016	-0.590	-2.57
8	-0.040	$+1.205$	5.31
20	-0.020	-0.257	-1.11
22	-0.032	$+0.917$	4.04

Notes: 4.46 V at the inputs of the AD620 instrumentation amplifier operated at a gain of 50.97. Thus, the equivalent phase shift for a quadrature output of 1 mV would be arctan $[0.001/(4.46*50.97)]=4.4\mu$rad.

(based on the assumption of a normal distribution) is $\pm 7.9\ \mu$rad. This demonstrates relatively good circuit stability under static conditions.

IV. DISCUSSION

We have described a measurement system which cancels displacement current to approximately one part in 10^5 with a feedback loop gain in the range of 1000 to 50 000 to maintain very low displacement current signal in spite of changes in sample capacitance. The primary imperfection results from the 2.5 pF capacitance of the photoresistor used in the variable resistive divider. Careful inspection and dissection of the photoresistor indicates that its parallel capacitance is inherent to the method of fabrication and tied to the minimum device resistance. In most applications, the displacement current will not change by large amounts during the experiment so that the phase shift caused by changes in the variable divider will be small. The phase stability of the variable divider could be improved by using a mechanically variable capacitor in a capacitive divider or, possibly, by placing a varactor diode across the bottom resistor of the present variable resistive divider with active feedback from a phase comparison to a fixed reference divider to adjust the varactor diode such that the phase output of the variable divider is the same as that of the reference divider. This would involve the addition of a reference divider, phase lock loop-based phase comparator, and varactor diode.

[1] C. Yokoyama, A. Wakisho, T. Sakamoto, K. Mori, and M. Nakagawa, Natl. Convention Record IEE Jpn. **7**, 275 (1995).
[2] M. Nagao, M. Kosaki, K. Tohyama, and T. Tokoro, IEEE Trans. Dielectr. Electr. Insul. **3**, 375 (1996).
[3] T. Tokoro, M. Nagao, and M. Kosaki, IEEE Trans. Electr. Insul. **27**, 482 (1992).
[4] Y. Yagi, H. Tanaka, and H. Kimura, 1998 Annual Report of the IEEE Conference on Electrical Insulation and Dielectric Phenomena, 1998, p. 653.
[5] J. Kawai, J. Shinaga, S. Nakamuram, K. Iida, and G. Sawa, 1998 Annual Report of the IEEE Conference on Electrical Insulation and Dielectric Phenomena, 1998, p. 637.
[6] T. C. Jordan and M. T. Shaw, IEEE Trans. Electr. Insul. **24**, 849 (1989).