MEASUREMENT RELIABILITY: THE DETECTION OF NONLINEARITIES

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Abstract

The detection of a single measurement failure in a compound measurement system consisting of a voltage divider and a Kerr cell is demonstrated. The comparison of measurement devices based on distinct technologies is inherently robust; they may be expected to have distinct failure characteristics. The Kerr comparison is based on model fitting applied to numerically-generated data and experimental, digitally-recorded waveforms. The characteristic signatures of two measurement errors are found: for a quadratic nonlinearity in the detector and for an overdriven photodetector. The length of the data records permits the detection of nonlinearities which are comparable to the noise in magnitude. Detection of such errors is a prerequisite to recalibration in software which enables error correction in remote applications, such as space power systems.

INTRODUCTION

The assurance of measurement reliability requires comparisons between metering devices and reference standards, together with systematic analysis of the sources of error. For space power applications, where the requirements of long life and assured readiness are pre-eminent, the ability to reliably monitor the state of a power system and, if necesssary, to remotely compensate for the drift and aging of sensors is of potentially great value. Already, the remote detection and correction of measurement errors has been investigated in the electrical power industry, which monitors its far-flung networks by telemetry (Adibi and Thorne 1986).

The recalibration process requires that the mode of failure be *identified* in order to be compensated. Otherwise, one performs an exercise in mere data fitting without reference to a reliable measurand. The identification problem requires an estimate of the actual response of any defective sensor so that its performance may be represented in a system model (Graupe 1976). With this objective in mind, we seek out those modes of failure which are most likely to occur in order to catalog them.

The present report demonstrates *detectibility* for a class of measurement failures by presenting the signatures for two types of nonlinearities in a compound voltage measurement system consisting of a Kerr-cell and a resistive voltage divider. These signatures are indicators of an out-of-calibration system. The resulting data may be useful as part of a heuristic for the detection of errors. While there is no guarantee of uniqueness to these signatures, two failures which are indistinguishible may permit identical corrections. The rigorous determination of corrections is left to a future paper.

EXPERIMENTAL SETUP

The experimental configuration used for this study is shown in Figure 1. The impulse generator is a pulse-forming network consisting of discrete inductors and capacitors that produces an output pulse having a 4-μs risetime. The Kerr cell is constructed of a polytetrafluoroethylene (PTFE) body with stainless steel plate electrodes and filled with purified nitrobenzene. It is connected in parallel with the precision resistive voltage divider to the output of the impulse generator. A stabilized helium-neon laser is used with a side-window photomultiplier tube (PMT) detector. The intensity variations that are measured by the PMT result from the rotation of the plane of polarization of the incident light beam induced by the Kerr liquid when the voltage is applied to the plates. The PMT has a highly nonlinear output for a dc supply voltage of 800 V, but the output is linear over a limited range of light intensities for a supply voltage of 360 V (Van Brunt 1990). The outputs of the resistive divider and PMT are measured with an 8-bit, dual channel, digitizing oscilloscope having a 100 MHz bandwidth.

The resistive divider has a low-inductance wirewound high voltage arm made by counter-winding identical lengths of a very low temperature coefficient resistive wire upon a cylindrical ceramic substrate. The low voltage arm is a discrete 2 W resistor selected to give a voltage divider ratio of approximately 5000:1. The divider is immersed in insulating oil to eliminate corona and to minimize the physical size required to withstand the full voltage (and subsequently minimize its response time). The response time of this precision divider to a step voltage having a risetime of a few nanoseconds is less than 10 ns.

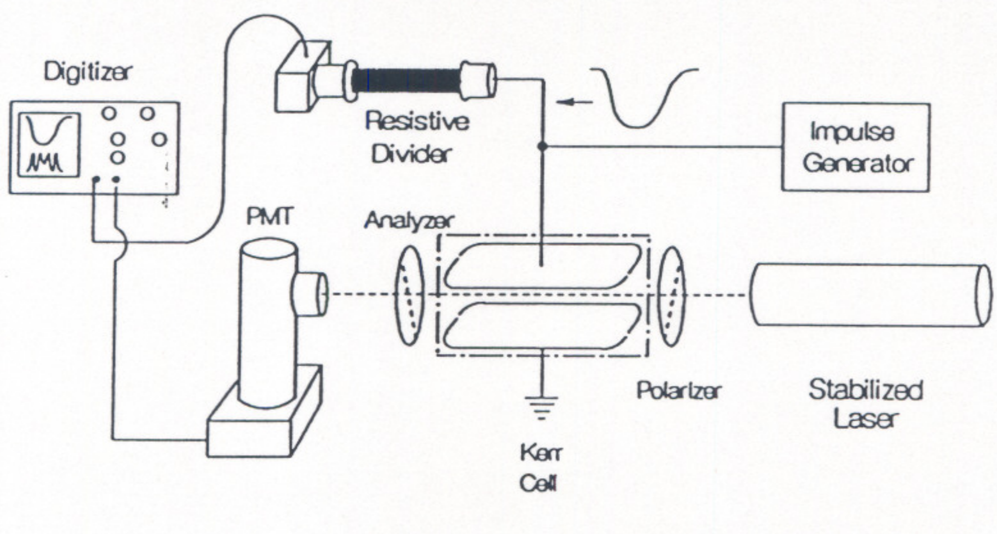

FIGURE 1. Experimental Configuration for Kerr-cell versus Resistive Divider Comparison.

The two waveforms which are acquired have the form as seen in Figure 2. The number of fringes in the Kerr photo-intensity is ideally related to the voltage by the Kerr law as described in the next section.

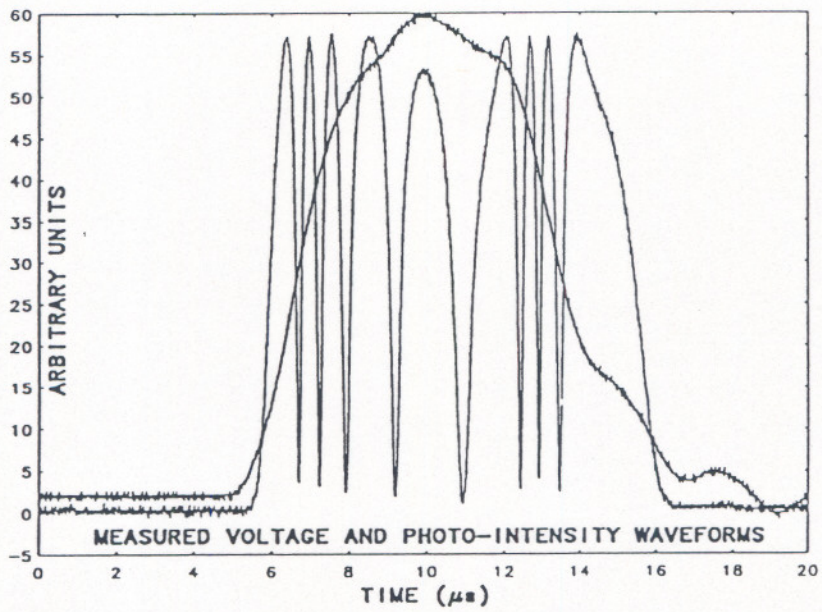

FIGURE 2. Simultaneous Display of Traces of the Voltage and Kerr Optical Waveforms for an Overdriven Detector. The General Fringe Pattern is Characteristic of Kerr-cell Measurements.

THE SYSTEM AND ITS NONLINEARITIES

The detection of nonlinearities is based on a numerical fitting of the coefficients in a model for the measurement system. The use of modern analytical techniques and the application of curve-fitting software to digital data allows for detectibility of nonlinearities at a level close to that of the intrinsic noise. The model for our system is based on the Kerr electro-optic effect. This effect produces a linear birefringence proportional to the square of the electric field. The result is to modulate the intensity of a beam at the output of the crossed polarizer system shown in Figure 1. In an ideal measurement system the path is fixed and the optical intensity, L, is is related to the voltage applied across the optical cell, U, by

$$L(t) = L_m \sin^2 \left\{ \frac{\pi}{2} \left(\frac{U(t)}{U_m} \right)^2 \right\}. \tag{1}$$

L_m is the maximum light intensity passed by the Kerr system and U_m is the Kerr cell constant which is determined by the Kerr coefficient and the cell geometry. The measured optical intensity, I, may differ from the intensity, L, and the measured voltage, V, may differ from the voltage, U, due to a variety of measurement errors, including nonlinearities. The signatures of two examples of such nonlinearities are given. These are: a quadratic nonlinearity in the photo-detector

$$I(t) = \alpha L + \beta L^2, \tag{2}$$

and the signature obtained from an overdriven detector operating outside its linear regime.

In the absence of any errors the Kerr Law (1) implies that at every instant of time the values of photo-intensity and of voltage will lie on the curve shown in Fig. 3 in the state space consisting of pairs (V,I). The coefficients, U_m and L_m which appear in the Kerr Law, may be determined from the data as a part of the nonlinear least squares fitting proceedure. This requires the minimization of the sum-of-squares lack-of fit for the discrete data expressed by

$$R^2 = \sum_{t_i} \left\{ L_m \sin^2 \left\{ \frac{\pi}{2} \left(\frac{V_i}{U_m} \right)^2 \right\} - I_i \right\}^2 . \tag{3}$$

The minimum is not unique; however, in many cases the desired values of U_m and L_m may be found as perturbations of the calibrated values. The fitting is based on the Levenberg-Marquardt algorithm for nonlinear optimization and employs the software, SUMSL, found in the public-domain Core Mathematical Library (CMLIB) (Boisvert, et al. 1984).

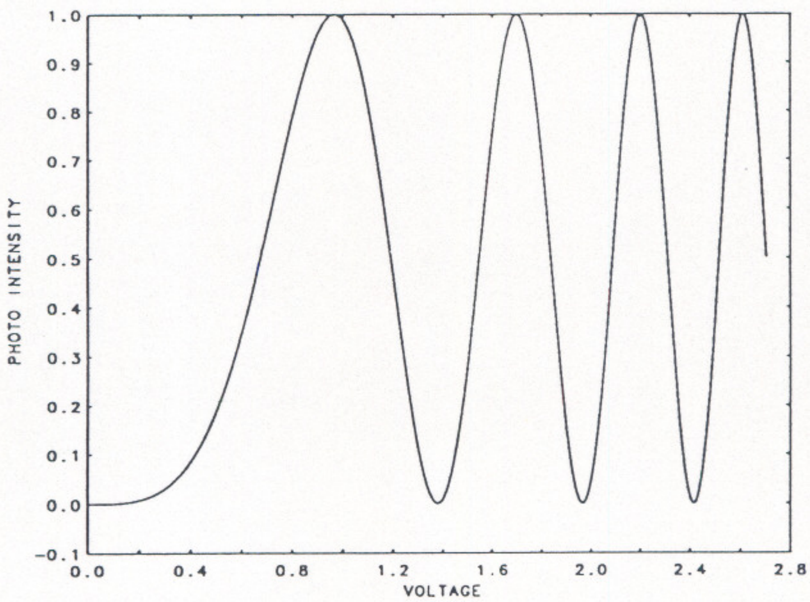

FIGURE 3. The Ideal Kerr-law Voltage-Intensity (U-L) Relationship with a Voltage Peak chosen to generate 7.5 Fringes. Time is absent from this plot and from the fitting procedure. The fitting minimizes the total residual between the measured voltage-intensity data and the U-L 'curve'.

RESULTS AND DISCUSSION

The signature of a nonlinearity in the detection system is found as the point-by-point lack-of-fit $I_i - L(V_i)$ as a function of L. In Figure 4a the result of this comparison is shown for a numerically-generated 0.25% quadratic nonlinearity in the photodetector, that is for value of $\alpha = 0.99, \beta = 0.01$ in Equation (2). In the absence of noise the signature of the failure is readily seen to be quadratic. Each branch of the residual plot corresponds to one fringe of

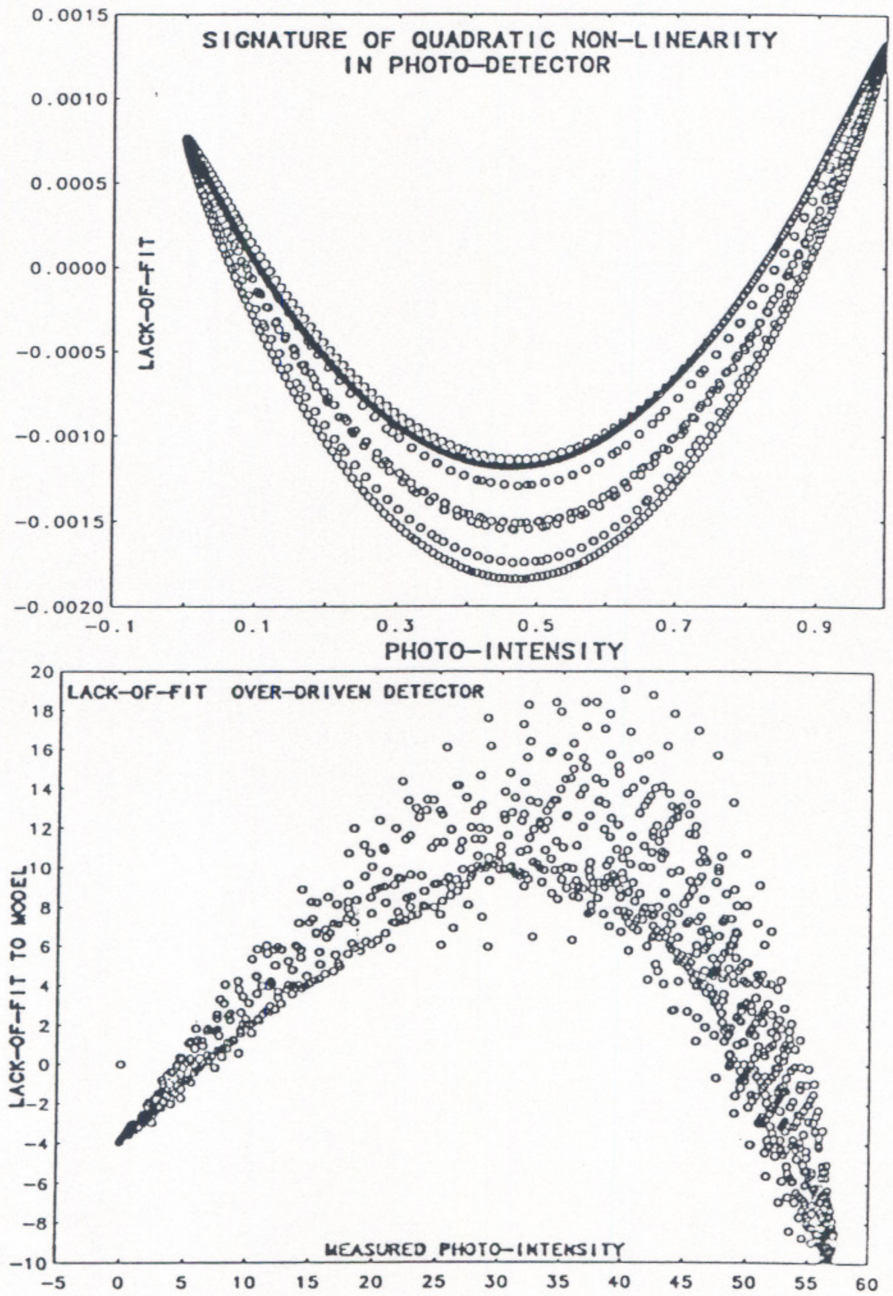

FIGURE 4. The Signatures of Nonlinearities arising from (a) a Simulated Quadratic Nonlinearity of 0.25% in the Photo-Detector, and (b) an Overdriven Photodetector - Experimental Data.

the Kerr intensity plot. In Figure 4b the results for experimentally introduced nonlinearity is shown. In this case the detector was overdriven at a voltage where the nonlinearity is to be expected (Van Brunt 1990). The noise of the system is not estimated independently. However, this characteristic pattern is seen for a range of over-voltages on the photodetector.

In each case the signature for an in-calibration system is a flat line with a noise level appropriate to the measurement system. The effect of noise on this detection heuristic is such that the nonlinearity can be observed when it is comparable to the noise. The large number of points permits averaging which effectively increases the signal-to-noise ratio.

CONCLUSIONS

The signatures for two types of measurement failure in a compound measurement system have been found. These are examples of the entries which collectively would form a catalog of the common modes of failure in the system under consideration. Possible applications of the technique are not confined to this system. It is intended to demonstrate the use of model fitting for the detection and, ultimately, the correction in software of systematic errors in a measurement system applied to remote power systems.

Acknowledgment

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