QUALIFYING WATTHOUR METERS FOR USE AS MAP TRANSPORT STANDARDS

J. D. Ramboz, C. Fenimore, and S. B. Schiller

National Institute of Standards and Technology
Gaithersburg, Maryland 20899

Abstract

One of the NIST Measurement Assurance Programs[1] transfers the watthour using transport meters. A statistical design is employed to determine the linear and non-linear corrections for the response of each meter to varying conditions of voltage, current, temperature, and power factor. For applications requiring less accuracy, a heuristic for dropping correction terms is given.

Introduction

Establishing 'traceability' between a measuring laboratory and the National Institute of Standards and Technology, NIST, traditionally involves sending an instrument to NIST for calibration. Alternatively, NIST sends one of its watthour transport standards to a laboratory. The laboratory performs a set of prescribed measurements, and returns the meter with the accumulated data. The measurement results are analyzed by NIST and an 'offset' is reported with which the laboratory corrects its standard to be in agreement with the National Standard. This interchange is known as a Measurement Assurance Program, MAP, for electric energy.

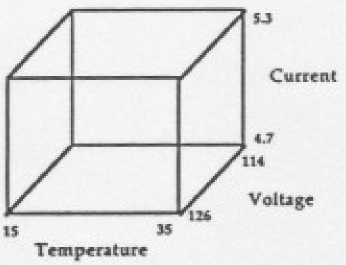
In such a measurement process, the absolute registration of the transport standard is relatively unimportant. The critical characteristic of the transport standard is its short term stability. Additionally, the devices to be used as transport standards are selected for their relative insensitivity to small changes in temperature, voltage, and current. Although the sensitivity of the meters may be small, the response must be characterized. Then the registration of the instrument can be corrected to a set of 'reference conditions'. This is done to achieve the best possible calibration of a laboratory's watthour standards and provides higher accuracy than is customary in the transfer of the unit of the watthour.

This paper describes the use of a statistically planned experiment to determine the effects of variations in temperature, voltage, and current at three power factors on a variety of commercially available watthour meters selected as transport standards. Previously the qualification process assumed the instrumental response to be linear[1], and the test points differed from reference conditions in only one variable at a time. Our process tests for non-linearities and interaction terms in the response. The test points are distributed over a design volume and are chosen to determine the statistically significant corrections with the minimum number of measurements.

Statistical Design

To 'qualify' a watthour meter for service as a MAP transport standard, NIST characterizes the meter's response for the range of conditions over which it typically will be used. The variables which affect the response of the watthour meters are found to be temperature, voltage, current, and power factor. Power factor takes on three values: 0.5 lag, 0.5 lead, and unity. The voltage, current, and temperature vary continuously, defining three design volumes, one for each power factor (Figure 1). The response can be represented as a surface over the design volume. For example, if values for current (I) and power factor are held fixed while voltage (V) and temperature (T) are varied, the response is a surface above the plane defined by changing voltage and temperature, as shown in figure 2. The correction of the registration to reference conditions is the difference between the height of this surface at the conditions actually encountered and the height of this surface at the reference conditions.

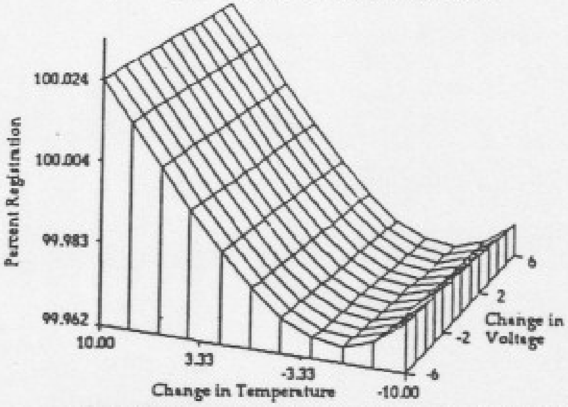
Figure 1: Control Volume



To choose a surface that simply and adequately describes the behavior of each transport standard, measurements are made for several design test points in the region described by the variables of interest. Then, using least squares, a surface is fit to the data. The remainder of the paper discusses test point and model selection.

The qualification process involves finding coefficients for ΔV, ΔI, and ΔT (changes in voltage, current, and temperature, respectively) and for products of these factors. Varying one factor at a time, it is not possible to determine whether interaction effects are present. Therefore, the experimental design includes measurements of percent registration made at reference conditions and at simultaneous deviations from reference for each continuous variable.

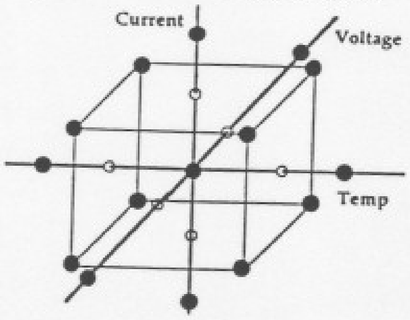
Figure 2: Cubic Model for Percent Registration



U.S. Government work not protected by U.S. copyright

The design region is: $(-6 \leq \Delta V \leq 6)$V, $(-0.3 \leq \Delta I \leq 0.3)$A, and $(-10 \leq \Delta T \leq 10)$°C. (The units are deviations from the reference values of 120 or 240 volts, 5 amperes, and 25°C). The initial design tests for two-way interactions between the variables and linear, quadratic and cubic terms for each. A 'box-star' experimental design[2] is employed which contains 15 points (figure 3). Eight of the design points are placed at outer corners of the region: (±6volts, ±0.3 amperes, ±10°C). One design point is placed at the center, and six more points are placed on the axes a little beyond the region of interest: $(\pm 10, 0, 0), (0, \pm 0.5, 0)$, and $(0, 0, \pm 15)$. Replicate measurements are made at each point. By spreading the design over the region of interest, the error in parameter estimates is reduced and the model is made applicable over the entire region.

Figure 3: Box-Star Design: 15 Points



Data is gathered according to this experimental plan. (In the first run, four transport standards were qualified.) A polynomial model is then fitted for each power factor for each watthour meter. The most complex model that can be fit (in terms of estimable parameters) is:

$$\begin{aligned}\%\text{Registration} \;=\; & a_1 + a_2\Delta T + a_3\Delta I + a_4\Delta V \\ & + a_5\Delta T^2 + a_6\Delta T^3 + a_7\Delta V^2 + a_8\Delta V^3 + a_9\Delta I^2 \\ & + a_{10}\Delta V\Delta T + a_{11}\Delta I\Delta T + a_{12}\Delta I\Delta V \qquad (1)\end{aligned}$$

As anticipated, this model is more complex than necessary to describe the data, because many of the parameter estimates are not significantly different from zero (i.e., some of the terms in the full model are negligible). Therefore, a stepwise procedure is used to determine the smallest model that adequately (in terms of statistical significance) describes the data. At each step, the procedure calculates a statistic (the F-statistic) for each term that reflects the contribution of that term to the model if it is included. The procedure adds the term that has the largest statistic and stops when none has a significance level greater than a preselected threshold[3]. For two of the meters, it is found that the simple linear model

$$\%\text{Registration} \;=\; a_1 + a_2\Delta T + a_3\Delta I + a_4\Delta V \qquad (2)$$

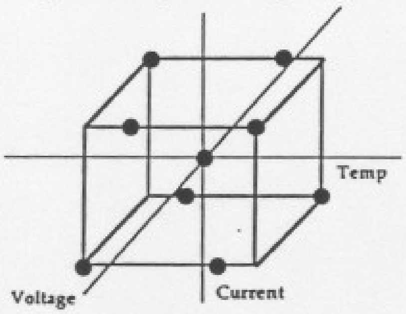
is, in fact, adequate because no other terms are statistically significant.

For the other two meters, a variety of terms in Eqn. (1) are found to be statistically significant; such terms vary from meter-to-meter and vary with power factor. An oversized design region has been chosen because the signal-to-noise ratio is otherwise too small to permit estimation of parameters in the actual test region. We exploit this fact in developing a heuristic to reduce the model. After fitting the full model and various reduced models, it is found that the simplest, adequate model for describing the response for these two meters in the actual test region is:

$$\begin{aligned}\%\text{Registration} \;=\; & a_1 + a_2\Delta T + a_3\Delta I + a_4\Delta V \\ & + a_5\Delta T^2 + a_6\Delta T^3 \qquad (3)\end{aligned}$$

Another four similar watthour meters were also to be characterized in this program. Knowing that temperature is the only variable for which higher-order terms are needed, the design may be reduced to fewer points. A D-optimal experimental design is used in the region of interest for the model in Eqn. 3 (figure 4). This design picks the set of n test points (here n is 9) in the design space which will permit estimation of the parameters of the given model with minimum variance[4]. The same heuristic may be applied to determine the simplest adequate model for each of these meters.

Figure 4: D-Optimal Design: 9 Points



Conclusions

The qualification of watthour meters for the MAP program requires that the response of these devices be found with high precision over a range of conditions of temperature, voltage, and current. Using a statistical experimental design, a significant increase in the information about each meter is achieved without a large increase in the effort expended. Of the eight meters characterized, four are described adequately by the linear model(Eqn. 2), while the other four require the cubic model(Eqn. 3). The statistical design and analysis provides a systematic method for characterizing the varied response characteristics of individual meters.

References

[1] N. M. Oldham, *A Measurement Assurance Program for Electric Energy*, Nat. Bur. Stand. (U.S.), Tech. Note 930 (Sept. 1976).

[2] D. C. Montgomery, *Design and Analysis of Experiments*, pp 462ff. Wiley (1984).

[3] Sanford Weisberg, *Applied Linear Regression*, 2nd ed., pp 211–215. Wiley (1985).

[4] T. J. Mitchell, "An Algorithm for the Construction of D-optimal Experimental Designs", *Technometrics*, 16, 203–210 (1983).