DESIRE: A Power Quality Prediction System

Steven R. Shaw Robert F. Lepard Steven B. Leeb, Member, IEEE

Laboratory for Electromagnetic and Electronic Systems
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

Abstract: *This paper describes a system for estimating the parameters of a simple model of an electric utility outlet using a transient measurement. Parameters of the utility model are estimated using data collected by the prototype. Nonlinear, frequency dependent effects observed in previous work in this area are accounted for with a physically based model. The performance of the entire system is demonstrated by comparison of measured and predicted line voltage distortion during current transients created by a laser printer.*

I. Background

From a service outlet, the electrical utility can be modeled as a sinusoidal voltage source in series with an inductor and a resistor. In a commercial or industrial building, impedances seen at the "user interface" arise predominantly from an upstream transformer, protection circuitry, and cabling. Harmonic currents generated by loads flow through these impedances, creating voltage drops that result in a distorted voltage waveform at the service outlet.

In [1], the authors present an ingenious technique for determining the local apparent impedance of the electrical utility service. The impedance is identified by briefly closing a capacitor across the electrical service at a precise point in the line voltage waveform. The shape and decay of the transient capacitor current in the resulting RLC circuit can be used to estimate the line impedance.

In this paper, the technique is reformulated in the DESIRE (Determination of Electrical Supply Inductance and Resistance) system for characterizing a local electrical service. This new system offers several advantages. The hardware features a power-level, digitally programmable test capacitor, a precision switch with a programmable firing angle, and a data collection interface. The flexibility of the DESIRE hardware, in particular its digital control, allows it to collect the data required to accurately characterize the local electrical service. The software uses methods we describe here to estimate the parameters of the local distribution service, given the transient test data generated by the DESIRE hardware. The estimation method is particularly attractive because it does not require calibration of the parasitics introduced by the DESIRE hardware. This paper also develops a model, motivated by theory, to account for the measured increase in utility resistance with increasing test frequency observed in [1]. The model is used to predict the characteristics of the service impedance over a wide range of frequencies, given a limited number of test measurements.

In [2] and [3], a transient event detector for nonintrusive load monitoring was introduced, which can determine in real time the operating schedule of the individual loads at a target site, strictly from measurements made at the electric utility service entry. With knowledge of the impedances of the distribution network in a building, collected by a one-time application of the DESIRE system, the nonintrusive load monitor could in many cases predict power quality (i.e., the extent of local voltage waveform distortion) using only information from the service entry. We conclude with a demonstration of this technique by predicting the local voltage waveform distortion created by a laser printer.

II. Service Model

In this paper, we examine a single phase, line-to-neutral connection to the electric utility. Electrical loads are presumed to be connected to the secondary of a single phase transformer driven at its primary by a stiff AC voltage source. Figure 1 shows a model for such a connection to the electric utility [1]. With certain simplifying assumptions, the resistance R and inductance L represent the composite impedances of cabling, protection circuitry, and the dominant transformer in the service stream. If the transformer is represented by a T-circuit model [4], the circuit in Fig. 1 can be developed as a Thevenin equivalent by assuming that $X_{mag} > (R_p + X_p)$, where X_{mag} and $R_p + X_p$ represent the reflected magnetizing and series primary impedances (series resistance and leakage inductance), respectively.

For low frequency power quality estimation, we are concerned with a frequency range from fundamental (60 Hz) to about 16th harmonic. Over this frequency range, the resistance R in Fig. 1 is a nonlinear, increasing function of frequency. The inductance in the model arises in part from the primary and secondary leakage inductances in the transformer, and also from stray fields around the cabling and conduits. The inductance is relatively independent of frequency. We assume that other parasitic components, especially inter- and intra-winding capacitances, have a negligible effect at the frequencies of interest, and are therefore

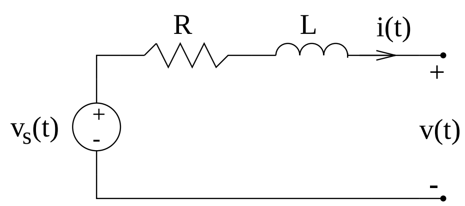

Figure 1: Utility model.

ignored. Extensions of the techniques in this paper to other situations, including a full three phase service, are possible.

III. DESIRE Prototype

To determine the effects of load currents on the voltage waveform, the parameters R and L of the utility model in Fig. 1 must be identified. The DESIRE prototype connects a capacitive load to the utility service and analyzes the resulting transient waveforms to determine these parameters. A circuit model of the system, including the electrical load created by the DESIRE prototype, is shown in Fig. 2.

The switch in Fig. 2 is controlled by a timing circuit that is phase-locked to the AC input voltage waveform. The firing angle of the switch can be programmed with 10-bit resolution, i.e., a resolution of one part in 1024 parts of a line cycle. Varying the firing angle allows the magnitude of the transient current $i(t)$ to be kept within the range of the current sensor. The value of the capacitor in Fig. 2 is also digitally programmable, with a resolution of seven bits. This is accomplished with a parallel array of seven fixed capacitors whose relative values are powers of two. The programmability of the switch firing angle and capacitor value in the DESIRE hardware permits the automated examination of transient current waveforms for a wide range of service power levels. It also facilitates rapid, computer-based data collection at a variety of transient frequencies. As will be shown in the following sections, accurate characterization of the frequency dependence of R in Fig. 1 depends on the ability to collect data at different transient frequencies.

For accurate power quality prediction, the estimation method must determine the impedances of the utility model independently of parasitic impedances in the DESIRE hardware. As modeled in Fig. 2, the DESIRE programmable switch contains parasitic resistance and inductance. The load shown in Fig. 2 is the the programmable capacitor, modeled with an equivalent series resistance. In the DESIRE prototype, no extreme effort was expended to minimize these parasitic elements or calibrate the test capacitances, since the parasitics are likely to depend on time, temperature and other environmental factors. The parameter estimation scheme described in the next section does not depend on any *a priori* knowledge of this kind.

IV. Parameter Estimation and Extrapolation

If measurements are made of $v(t)$, $v_s(t)$ and $i(t)$, as indicated in Fig. 2, the unknown parameters R and L of the utility model can be estimated. Because the parameters R and L are unknown,the voltage $v_s(t)$ can only be measured when $i(t)$ is zero, which precludes direct measurement during the transient. For practical purposes, we assume that $v_s(t)$ is shift invariant over a small integer multiple n of the fundamental period T, i.e. $v_s(t) \approx v_s(t+nT)$. By collecting reference waveforms immediately before performing a transient test, which is easily accomplished with a computerized data acquisition system, the shift nT above can be made quite small. Note that the requirement that $i(t) = 0$ does not imply that the transformer is unloaded. The transformer load need only be in steady state over the short interval required to collect $v_s(t)$ and perform the transient test. Measurement of $i(t)$ and $v(t)$ during the transient is straightforward.

Identification of the parameters R and L

Assuming that $v_s(t)$ is shift invariant as above, the parameters R and L constrain the signals $v(t)$, $i(t)$, and $v_s(t)$ according to the relationship in Eqn. 1. In the following, p represents the differentiation operator $\frac{d}{dt}$:

$$v_s(t) - v(t) = (R + Lp)i(t). \tag{1}$$

The parameters R and L could be found directly from Eqn. 1 if the continuous time current waveform were available and could be differentiated accurately. The measured data, however, consists of the samples $i(nT_s)$, $v(nT_s)$, and $v_s(nT_s)$, where T_s is the sampling period. We eliminate the problems associated with measuring or approximating the derivatives in Eqn. 1 by introducing the causal, "low-pass" operator λ, with $\tau > 0$, [5]:

$$\lambda = \frac{1}{1 + p\tau}. \tag{2}$$

Solving Eqn. 2 for p, we obtain the following:

$$p = \frac{1 - \lambda}{\lambda\tau}. \tag{3}$$

Equation 1 can be reformulated by substitution with Eqn. 3 to produce a linear least squares tableau that can be used to estimate R and L:

$$\begin{pmatrix} [\tau\lambda(v_s - v)](t) \\ [-\tau\lambda i](t) \end{pmatrix}^T \begin{pmatrix} \hat{\beta_1} \\ \hat{\beta_2} \end{pmatrix} = i(t), \tag{4}$$

where $\hat{\beta_1}$ and $\hat{\beta_2}$ are estimates of $\frac{1}{L}$ and $\frac{R}{L}$, respectively. The notation $[\lambda i](t)$ indicates the row vector $([\lambda i](T), [\lambda i](2T)...[\lambda i](NT))$, where $[\lambda i](t)$ is the result of applying λ to $i(t)$ at time t. Although λ is a continuous time operator, we have found that it can be applied off-line to linear or zero-order hold interpolations of the finely sampled quantities with little error. It is desirable to apply λ to sampled data for reasons of implementation. The

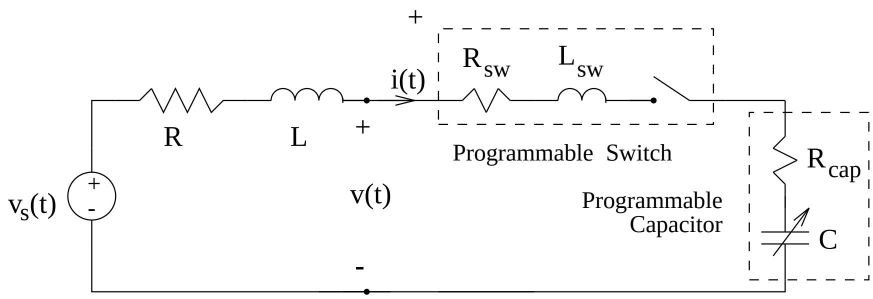

Figure 2: DESIRE hardware.

time constant τ associated with λ must be determined by the user. The time constant should be chosen to preserve information content, and also so that the effects of noise in the regressors and the errors associated with interpolation of the sampled data are minimized. All of the results presented here were obtained using $\tau = .002$s. In practice, a relatively wide range of values of τ produces satisfactory estimates.

Equation 4 is arranged to minimize the bias in the parameter estimate introduced by disturbances in the measurements. In particular, the regressors are picked so that they are low-pass. Unless disturbances are pathologically low-pass, the error in the filtered regressors will be substantially uncorrelated to the unfiltered right-hand side. If the disturbances are symmetrically distributed and uncorrelated to the regressors, for large N the estimates will be unbiased. A more thorough discussion of the role of noise in this method can be found in [5].

Estimating transient frequency

It is important to associate a frequency f with the parameter R found by the methods outlined above, as R is a function of frequency. We account for the parasitic elements in Fig. 2 by defining quantities $R_{tot} = R + R_{sw} + R_{cap}$ and $L_{tot} = L + L_{sw}$. The transient frequency f (in Hertz) is given by Eqn. 5 in terms of these new parameters.

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{L_{tot}C} - \frac{R_{tot}^2}{4L_{tot}^2}} \qquad (5)$$

One approach to find the estimate $\hat{f}$, therefore, is to first determine the unknown parameters R_{tot}, L_{tot}, and C and then use Eqn. 5. This technique is preferable to timing zero crossings, for example, because it is relatively insensitive to noise at the zero crossings and is independent of the steady state response.

To find the estimates $\hat{R_{tot}}$, $\hat{L_{tot}}$, and $\hat{C}$, we employ the λ-operator substitution technique to the equation relating $i(t)$ to $v_s(t)$ in Fig. 2:

$$v_s(t) = (R_{tot} + L_{tot}p + \frac{1}{Cp})i(t). \qquad (6)$$

Substitution to eliminate p yields the following equation in terms of the operator λ and its parameter τ.

$$\begin{pmatrix} [\tau(\lambda-\lambda^2)i](t) \\ [\tau^2\lambda^2 i](t) \\ [\tau(\lambda^2-\lambda)v_s](t) \end{pmatrix}^T \begin{pmatrix} \hat{\alpha_1} \\ \hat{\alpha_2} \\ \hat{\alpha_3} \end{pmatrix} = [-i + 2\lambda i - \lambda^2 i](t) \qquad (7)$$

where $\hat{\alpha_1}$, $\hat{\alpha_2}$ and $\hat{\alpha_3}$ are estimates of $\frac{R_{tot}}{L_{tot}}$, $\frac{L_{tot}}{C}$, and $\frac{1}{L_{tot}}$, respectively. Equation 7 is solved in a least-squares sense and the parameter estimates are used to compute the transient frequency f using Eqn. 5.

V. Frequency dependence of R

In [1] and in the experiments in our laboratory, the apparent resistance R was observed to be an increasing function of the frequency f of the transient. Phenomena that could explain this observation include, for example, eddy currents induced in conductors adjacent to current carrying wires and skin effect in the wires themselves.

In [6] the change of resistance due to the skinning effect in a conductor with cylindrical geometry is given for $x \ll 1$ ("low" frequencies) as

$$\frac{R}{R_0} \approx 1 + \frac{x^4}{192} \qquad (8)$$

where $x \propto \sqrt{f}$ and the constant of proportionality, given explicitly in [6], is related to the physical properties and geometry of the conductor. R_0 is the DC resistance.

From [6], eddy currents in conductive materials adjacent to current carrying wires produce changes in effective resistance as in Eqn. 9, which is valid for $\theta \ll 1$.

$$R \approx R_0 + 2\pi f L_0 \frac{\theta^2}{6} \qquad (9)$$

Here, $\theta \propto \sqrt{f}$. Again, the constant of proportionality is geometry and material dependent, and can be found analytically for certain geometries.

Assuming that the constants relating x and θ to $\sqrt{f}$ are favorably scaled, Equations 8 and 9 suggest the following fitting function, with parameters R_0 and δ.

$$R(f) = R_0 + \delta f^2 \qquad (10)$$

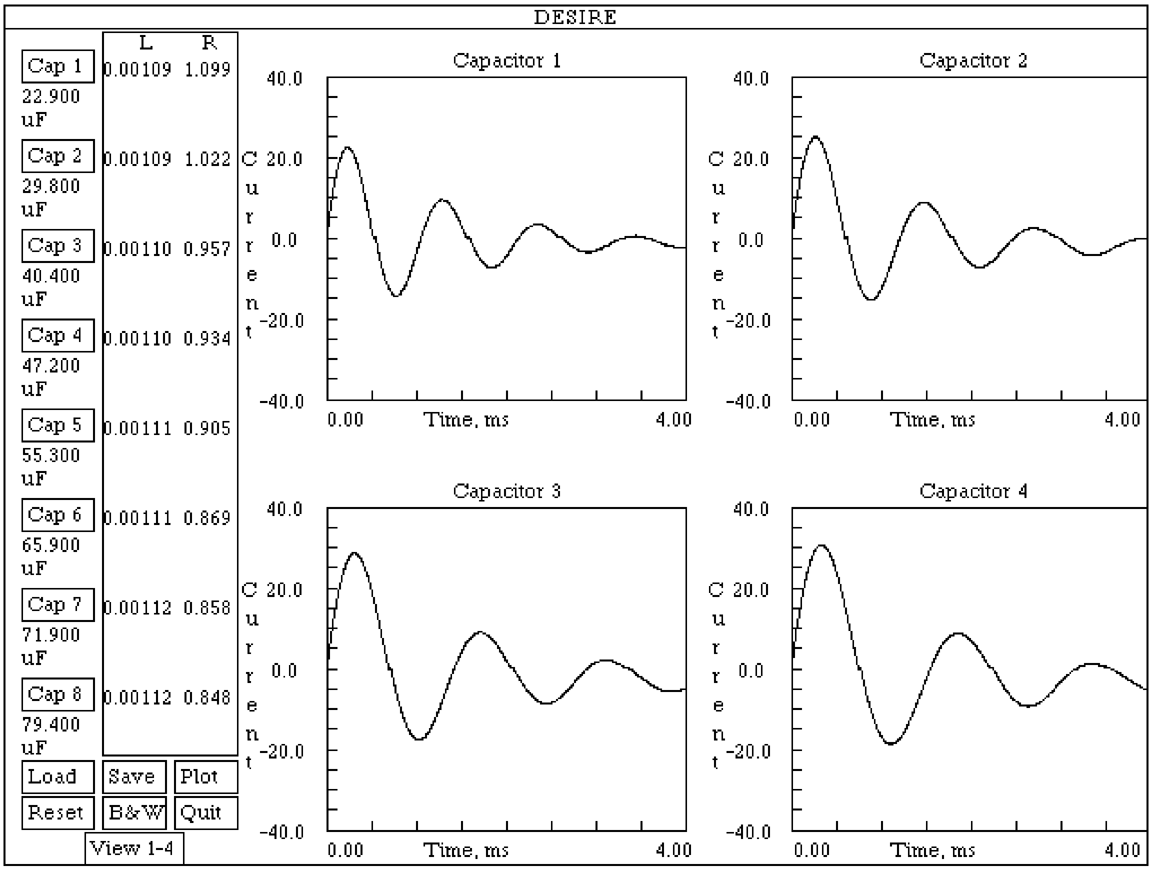

Figure 3: Screen interaction with DESIRE prototype.

With several estimates $\hat{R}(f)$ made at different frequencies, a least-squares solution for the parameters $\hat{R}_0$ and $\hat{\delta}$ can be found which satisfies Eqn. 10. Transient tests at different frequencies can be automatically conducted by the DESIRE system simply by programming a range of values for C. It may be possible, based on the value of δ, to determine frequencies above which Eqn. 10 becomes invalid. However, this was not investigated in detail here because the purpose is to extrapolate the data to *lower* frequencies, and because the collected data at higher frequencies are well interpolated by Eqn. 10.

VI. Experimental Results

The test setup used to validate the DESIRE hardware and software consisted of a single phase 1 kVA isolation transformer connected between phase and neutral of a three-phase 60 Hz, 30 A per phase, electrical service. A relatively small transformer was chosen so that it could be removed from service and characterized independently during development. After the transformer was characterized using the DESIRE system, a laser printer with a base plate rating of 7.6 A at 115 VAC RMS was connected to the transformer. Given the laser printer's remarkable current waveform, we predict the voltage distortion due to the service parameters $R(f)$ and L.

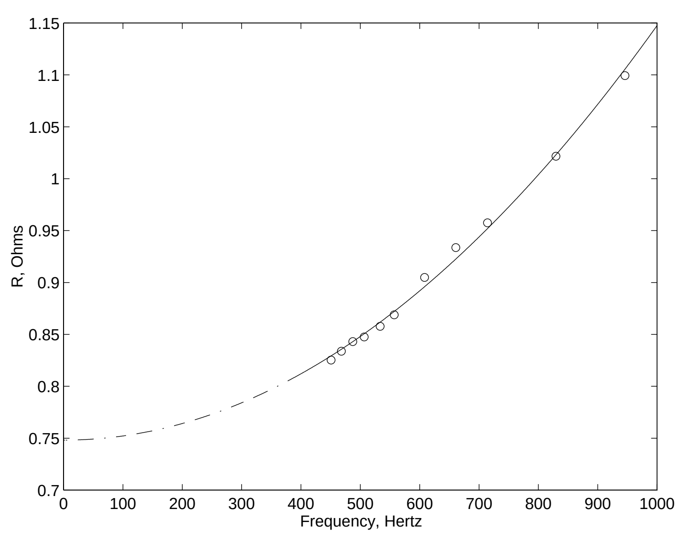

Figure 4: Resistance R as a function of frequency f.

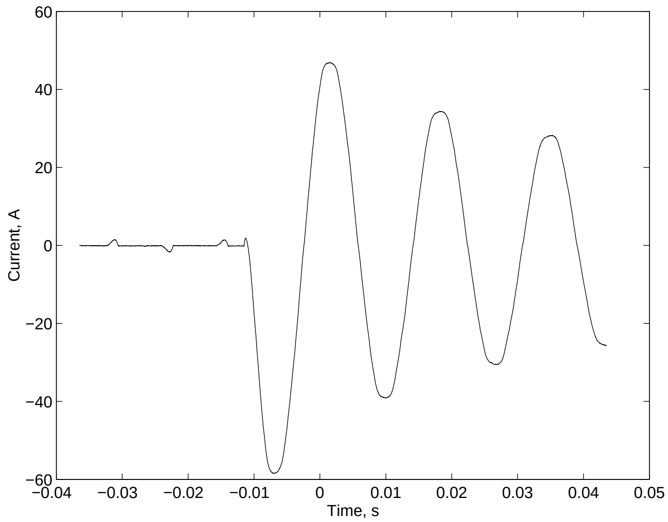

Figure 5: Sample current transient.

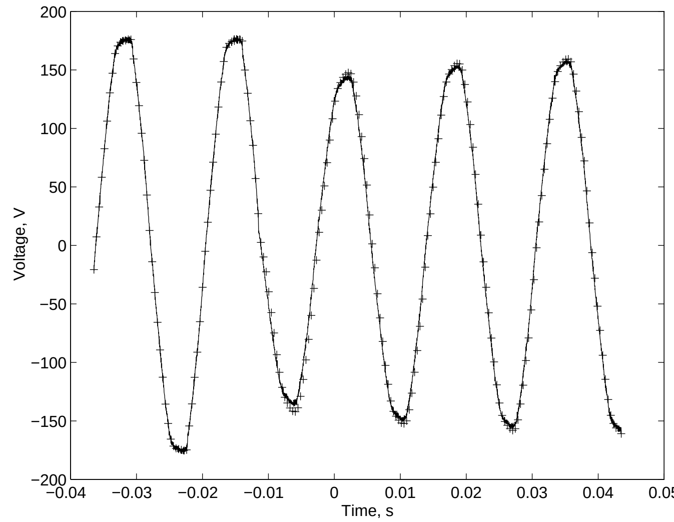

Figure 6: Measured and predicted line voltage distortion.

Figure 3 shows a screen interaction with the DESIRE system. DESIRE can be configured to conduct eight transient measurements on a utility connection automatically. The user selects nominal capacitor values which will be connected across the utility. The estimated capacitor values used during the tests are shown at the far left hand side of the screen in Fig. 3. The transient currents during each of the experiments are plotted on the right hand side of the screen for four of the eight different capacitor values. The user may view either the first or second set of four transient plots. The estimated values of R and L for the the service model are displayed to the left of the transient current plots.

Fig. 4 shows estimated resistance $\hat{R}$ as a function of transient frequency f (Hz). The solid line is the interpolation of the data according to the model of Eqn. 10, and the dashed line shows the extrapolation of the model to lower frequencies. The estimated inductance $\hat{L}$ was 1.10 mH.

Fig. 5 shows a transient current waveform drawn by the printer during operation.

In Fig. 6, the measured and predicted line voltages are displayed. The data points show the measured voltage waveform, decimated for clarity. The solid line is a linear interpolation of the simulation results.

The predicted data was obtained using the estimate $\hat{L}$, the extrapolation of Eqn. 10 to 60 Hertz using the data in Fig. 4, the measured current $i(t)$, and Eqn. 1.

VII. Conclusions

The DESIRE prototype and analysis software provide a flexible system for characterizing the effective impedance of a utility service connection. This information can be used for a variety of applications by utilities, and also commercial and industrial facilities managers. In [2], the nonintrusive load monitor was demonstrated to have the ability to disaggregate the operating schedule of individual loads given access only to the aggregate current waveforms at the service entry. With additional knowledge collected during a one-time (or at least infrequent) examination of the details of a building's wiring harness, the location of loads on the harness, and the service connection impedances as determined by the DESIRE system, the nonintrusive load monitor could provide continuous prediction of the local voltage waveform at points of interest. We have demonstrated the basis for this power quality monitoring technique in this paper.

The impedance calculations made by DESIRE could also be used, for example, to compute the available fault currents at a service connection. This information would help to verify the proper rating of protection circuitry in the wiring harness. During our experimentation, we have observed that careful, high sample rate examination of the transient current waveforms collected by DESIRE reveal additional, very high frequency ringing that we suspect can be attributed to neglected elements in the utility model, e.g., inter- and intra-winding capacitances. It is conceivable that additional information about the utility service impedance could be determined by DESIRE, which might be useful for determining the propagation of high frequency EMI or power line carrier modem signals.

Acknowledgments

This research was funded by the Office of Research and Development, a CAREER award from the National Science Foundation, and MIT's Carl Richard Soderberg Career Development Chair. The authors gratefully acknowledge the valuable advice and support of Deron K. Jackson, Professors James L. Kirtley, Jr., George Verghese, Bernie Lesieutre, and Les Norford and Doctors Craig Searles and Dave Charvonia.

Essential hardware for this project was made available through a generous donation from the Intel Corporation. Test and measurement equipment were generously supplied by Tektronix and Hewlett-Packard.

References

[1] Beattie, W.C. and S.R. Matthews. "Impedance measurement on distribution networks", *Proceedings of the 29th Universities Power Engineering Conference*, pp. 117-120, September 1994.

[2] Leeb, S.B., S.R. Shaw, J.L. Kirtley, Jr., "Transient Event Detection in Spectral Envelope Estimates for Nonintrusive Load Monitoring," *IEEE Transactions on Power Delivery*, Volume 10, Number 3, pp. 1200-1210, July 1995.

[3] Leeb, S.B., and J.L. Kirtley, Jr., "A Transient Event Detector for Nonintrusive Load Monitoring," U.S. Patent Number 5,483,153, issued January 9, 1996.

[4] Slemon, G.R., *Magnetoelectric Devices: Transducers, Transformers, and Machines*, John–Wiley and Sons, 1966.

[5] Johansson, Rolf., *System Modeling and Identification*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, pp. 283-293, 1993.

[6] Bozorth, Richard M. *Ferromagnetism*, D. Van Nostrand Company, Inc. Princeton, New Jersey, pp. 774-778, 1959.

Steven R. Shaw is a graduate research assistant in the Laboratory for Electromagnetic and Electronic Systems at the Massachusetts Institute of Technology. He received his Bachelor of Science degree in Electrical Engineering from M.I.T. in June, 1995.

Rob Lepard, originally from Cincinnati, OH, graduated from the Massachusetts Institute of Technology with a Bachelor of Science and Master of Engineering Degree in Electrical Engineering in June, 1996. He is currently serving the the United States Air Force as a Second Lieutenant in the Aeronautical Systems Command, and is stationed at Wright-Patterson AFB.

Steven B. Leeb (S'89-M'93) received his Bachelor of Science, Master of Science, Electrical Engineer, and Doctoral degrees from the Massachusetts Institute of Technology in 1987, 1989, 1990, and 1993, respectively. He has been a member of the M.I.T. faculty in the Department of Electrical Engineering and Computer Science since 1993. He currently serves as the Carl Richard Soderberg Assistant Professor of Power Engineering in the Laboratory for Electromagnetic and Electronic Systems.

Dr. Leeb is concerned with the design, analysis, development, and maintenance processes for all kinds of machinery with electrical actuators, sensors, or power electronic drives. He is a member of the IEEE Power Engineering Society, a Fellow of M.I.T.'s Leader's for Manufacturing Program, and a member of Tau Beta Pi and Eta Kappa Nu.