# Accuracy Evaluation in Power Hardware-in-the-Loop (PHIL) Simulation

Center for Advanced Power Systems

W. Ren, *Student Member, IEEE*
rren@caps.fsu.edu
2000 Levy Ave., Tallahassee, FL, 32310

M. Steurer, *Senior Member, IEEE*
steurer@caps.fsu.edu
2000 Levy Ave., Tallahassee, FL, 32310

S. Woodruff
woodruff@caps.fsu.edu
2000 Levy Ave., Tallahassee, FL, 32310

**Keywords —** Hardware-in-the-Loop simulation, simulation accuracy

**Abstract —** The inherent non-idealities, especially the time delay, in the interface of a PHIL simulation may lead to large simulation errors or even instabilities. Therefore, it is extremely important to have an effective way to evaluate the simulation accuracy in order to justify the reliability of a PHIL experiment. A generalized metric defining the error functions from two types of PHIL interface perturbations is proposed in this paper. Two simulation examples are performed to show the validity of the proposed method.

## 1 Introduction

Power hardware-in-the-loop (PHIL) simulation, where a piece of hardware equipment is incorporated into a simulation of a large system, provides many advantages that other analysis and testing methods do not provide. The most significant of these advantages are the ability to perform dynamic tests of the hardware device in an accurate representation of its service environment and the ability to conduct system studies incorporating the device. Therefore, it is receiving increased interest in power system and power electronics applications. In a PHIL simulation, a power apparatus can directly interact with a simulated environment. The dynamic and transient behaviors of the apparatus together with the simulated system are thoroughly investigated under all conceivable operating conditions. Hidden design flaws and defects can be detected and inadequate models can be refined while experimental risk and cost are minimized. A number of PHIL applications have been reported in [1]-[4]. A unique 5 MW PHIL test bed is being established at the Center for Advanced Power Systems (CAPS) at Florida State University (FSU) to enable high-power PHIL experiments for comprehensive testing of power system components interacting with simulated all-electric ship power systems.

However, due to the non-idealities of the interface between the hardware and software parts of the system, especially time delays, a PHIL simulation may be subject to artificial instabilities. (That is, instabilities that are artefacts of the test setup and are not present in a real system involving the test device and a hardware implementation of the simulated system.) An analytical explanation of the PHIL stability issue and advice on how to improve the PHIL stability via applying various interface algorithms are given in [5]. Furthermore, even a stable PHIL system does not necessarily ensure a meaningful simulation. The simulation must also be accurate to produce useful results. In fact, accuracy is the primary consideration in setting up a PHIL simulation, since instability can be considered as an extreme condition of inaccuracy.

Evaluating the PHIL simulation accuracy is not trivial because no benchmark system is available for reference. Even if simulation models of the hardware under test (HUT) exist they will never match the hardware characteristic exactly. Otherwise, the correct result is already known and the PHIL simulation becomes unnecessary. [6] discussed the idea of using "transparency performance index" to evaluate the fidelity of an HIL simulation. This approach compares the difference between the actual HUT impedance and the equivalent HUT impedance seen from the other side of the interface. Smaller difference indicates higher transparency of the interface. However, this approach focuses on the performance of the interface only and neglects the fact that a PHIL simulation is a closed loop system. Therefore, it has limited applicability because we can easily find counterexamples (e.g., the unstable PHIL example discussed in [5]) in which high transparency may also lead to large simulation error. Two concepts of "performance mismatch (PMM)" and "probability of PMM" were described in [7] to evaluate the simulation performance. But the discussion stops at an abstract level, making it difficult to be applied in practice.

In this paper, a metric for PHIL accuracy evaluation is established. Since the simulation error mainly comes from the perturbation caused by the non-ideal PHIL interface, the presented metric focuses on this type of error. The perturbations are categorized in two different types and an error function for evaluating each perturbation is defined. To validate the results, two simulation examples are given. As we show below, the proposed metric provides an effective approach to evaluating the accuracy of a PHIL simulation in practice.

## 2 Interface Transfer Function Perturbation

Interface transfer function perturbation (TFP) is the first type of perturbation we will discuss in this paper. It expresses the non-ideality of a PHIL interface as a transfer function differing from unity gain. Examples of TFP include the time delay, the low pass filter properties, and any frequency characteristics other than unity gain of the PHIL interface.

### 2.1 TFP for Open Loop Systems

To evaluate the error caused by the TFP we start from a simple open-loop case in **Figure 1**. In this system, x is the input, G(s) is the correct (or desired) transfer function of the system while $\Delta G$ represents a transfer function perturbation.

The correct system output is y and the error caused by the perturbation is Δy. Note that G(s) here is a general transfer function and not the transfer function of the PHIL interface. Typically, G(s) relates two quantities in the simulation with each other.

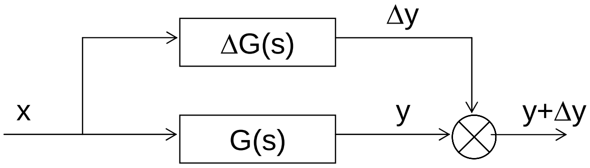


**Figure 1**: An open loop system with a TFP (ΔG)

A reasonable approach to evaluate the accuracy of this system is to compare the magnitude of Δy and y in the frequency domain. Assume an input,

$$x(t) = x_0 e^{j\omega t} \tag{1}$$

is present, we will then have

$$\frac{|\Delta y(j\omega)|}{|y(j\omega)|} = \frac{|\Delta G(j\omega) x_0 e^{j\omega t}|}{|G(j\omega) x_0 e^{j\omega t}|} = \left|\frac{\Delta G(j\omega)}{G(j\omega)}\right|. \tag{2}$$

An error function $E_{TFP}$ is defined as

$$E_{TFP} = \left|\frac{\Delta G(j\omega)}{G(j\omega)}\right| \tag{3}$$

The maximum value of $E_{TFP}$ within the frequency domain of interest signifies the largest error in the simulation,

$$\overline{E}_{TFP} = \sup_{\omega}(E_{TFP}) \tag{4}$$

where "sup" stands for "supremum".

When different accuracy levels are required at different frequencies a weighting function $W_O(j\omega)$ can be multiplied with the error function as shown in (5).

$$E_{TFP} = \left| W_O(j\omega) \frac{\Delta G(j\omega)}{G(j\omega)} \right| \tag{5}$$

## 2.2 TFP for PHIL Systems

The error function derived in the last section can not be directly applied to closed-loop systems (e.g., a PHIL system). To find the equivalent ΔG and G in a PHIL system, we consider the generalized block diagram of a PHIL system shown in **Figure 2**. $G_1$ to $G_4$ represent the transfer functions of the simulation systems and the hardware under test. Since an ideal PHIL interface has unity gain, zero time delay and infinite bandwidth, we use "1" as the desired transfer function of the PHIL interface and use an additive $\Delta G_{int}(s)$ as its perturbation. As we will show later, the system output of interest can only be either $y_1$ or $y_2$ by appropriately defining the blocks from $G_1$ to $G_4$. The derived result is regardless to the individual expression of $G_1$ to $G_4$. In order to study the simulation accuracy, we will derive the error function for each of the two outputs.

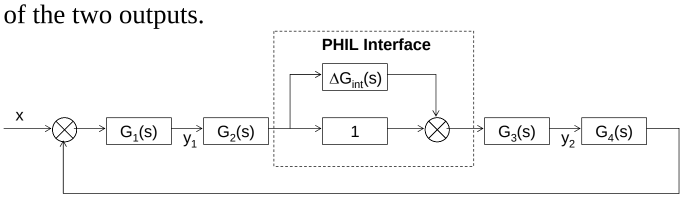


**Figure 2**: A PHIL system with TFP ($\Delta G_{int}$)

Assuming $y_1$ as the system output of interest and an input according to (1), the correct result of $y_1$ when there is no TFP is:

$$y_1(t) = \frac{G_1(j\omega)}{1 - G_4(j\omega)G_3(j\omega)G_2(j\omega)G_1(j\omega)} x_0 e^{j\omega t}, \tag{6}$$
$$= \frac{G_1(j\omega)}{1 - G_{LP}(j\omega)} x_0 e^{j\omega t}$$

where $G_{LP}(j\omega) = G_4(j\omega)G_3(j\omega)G_2(j\omega)G_1(j\omega)$ is the system open loop transfer function. In comparison, the resulting $y_1$ with the interface perturbation is:

$$y_1(t) + \Delta y_1(t) = \frac{G_1}{1 - G_4 G_3 (1 + \Delta G_{\text{int}}) G_2 G_1} x_0 e^{j\omega t} \tag{7}$$
$$= \frac{G_1}{1 - G_{LP}(1 + \Delta G_{\text{int}})} x_0 e^{j\omega t}$$

For simplicity, the argument "jω" is omitted from the equation above. By combining (6) and (7), we derive:

$$\Delta y_1(t) = \frac{G_1}{1 - G_{LP}} \frac{G_{LP} \Delta G_{\text{int}}}{1 - G_{LP}(1 + \Delta G_{\text{int}})} x_0 e^{j\omega t} \tag{8}$$

and

$$E_{TFP\_y1} = \left| W_O \frac{G_{LP} \Delta G_{\text{int}}}{1 - G_{LP}(1 + \Delta G_{\text{int}})} \right| \tag{9}$$

The error function derivation for $y_2$ can be done in the same manner.

$$E_{TFP\_y2} = \left| W_O \frac{\Delta G_{\text{int}}}{1 - G_{LP}(1 + \Delta G_{\text{int}})} \right| \tag{10}$$

It is interesting to note that both error functions are only determined by the product of $G_1$ to $G_4$ (the open loop transfer function $G_{LP}$) instead of their individual expressions. This fact backwardly validates the generality of the system block diagram in Figure 2.

The choice between $E_{TFP\_y1}$ or $E_{TFP\_y2}$ for accuracy evaluation depends on which system responses are of interest. It is also possible to combine the two error functions together as shown in (11) to find the maximum simulation error.

$$E_{TFP} = \max(E_{TFP\_y1}, E_{TFP\_y2}) \tag{11}$$

# 3 INTERFACE NOISE PERTURBATION

In contrast to the TFP, another type of interface perturbation comes directly from external noises injected into the system. The noise does not influence the system input *x* but will influence the system output y. We therefore distinguish this type of perturbation as an interface noise perturbation (NP). A NP may come from the high frequency harmonics generated by a PWM interface amplifier, the sensor noise or distortions in the signal transmissions.

The error caused by a NP can be computed via the transfer function from that noise source to a certain output under interest. Suppose we know the magnitude of a noise and express it as $v_0 e^{j\omega t}$, we then have

$$\Delta y = G_{yv}(j\omega) v_0 e^{j\omega t} \tag{12}$$

as the error in the system output due to that noise. In this equation, $G_{yv}$ represents the transfer function between noise *v* to output *y*. Again, the simulation accuracy can be evaluated from comparing the magnitude of the error and the original system output

$$\frac{|\Delta y|}{|y|}=\frac{|G_{yv}(j\omega)v_0 e^{j\omega t}|}{|y|}=\frac{|G_{yv}(j\omega)|\,v_0}{|y|}. \tag{13}$$

Since the noise source is independent of the system transfer function, we have to find a way to evaluate the magnitude of $v_0$ and $y$. By expressing $v_0$ as the multiplication of an input weighting function $W_I(j\omega)$ and a normalized signal $v_0$' which has the same magnitude as $y$,

$$v_0 = W_I(j\omega)v'_0 \tag{14}$$

we can then define the error function for this NP

$$E_{NP}=\frac{|\Delta y|}{|y|}=\frac{|G_{yv}(j\omega)|W_I(j\omega)v'_0}{|y|}. \tag{15}$$

$$\approx |G_{yu}(j\omega)W_I(j\omega)|$$

Again, if different accuracy levels are required at different frequencies, an output weighting function $W_O$ (jω) can be included in the NP type error function, yielding

$$E_{NP}=|W_O(j\omega)G_{yu}(j\omega)W_I(j\omega)|. \tag{16}$$

Although the cancellation of $v'_0$ and $y$ is done mainly by approximation instead of by precise mathematical derivation, the NP error function provides a feasible approach to studying this type of simulation accuracy problem.

## 4 SIMULATION EXAMPLES

### 4.1 A TFP Type PHIL Accuracy Evaluation Example

A PHIL simulation is performed to study the dynamic behavior of a simple resistive-inductive circuit. As shown in **Figure 3** the original circuit is separated in to two parts. The voltage source $v_S$ and the source resistor $R_S$ are simulated in a real time simulator, while the load reactor $L_L$ and resistor $R_L$ are replaced by real hardware. To facilitate the interconnection between the two parts an ideal transformer model [5] is used. A voltage amplifier reproduces the "simulated" voltage ($v_1$) as a "real" voltage ($v_2$) and imposes it onto the load. The actual current ($i_2$), drawn by the load, is measured and fed back into the simulated circuit by means of a modeled current source ($i_1$).

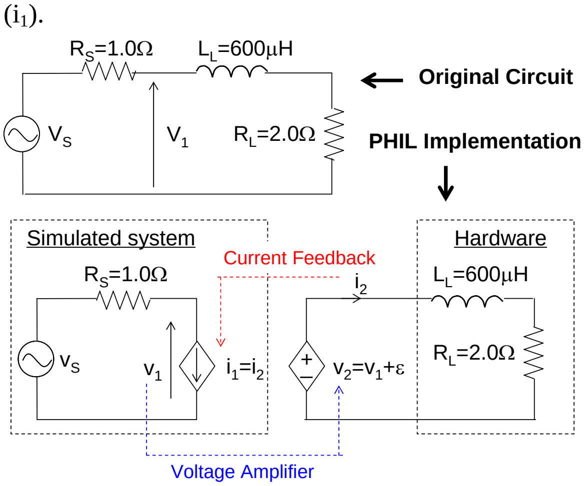


**Figure 3**: A RL load PHIL system

Assuming all the interface signals are transmitted ideally except for a simple time delay in the voltage amplification, we are able to draw the system block diagram in **Figure 4**.

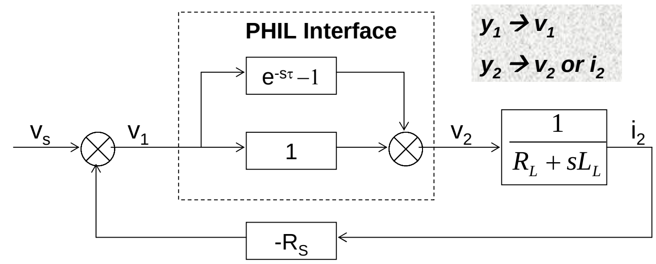


**Figure 4**: System block diagram

The accuracy evaluation of this system therefore becomes a TFP type problem. From the block diagram we derive

$$\Delta G_{\text{int}} = e^{-s\tau} - 1$$

and

$$G_{LP}=\frac{-R_S}{R_L+L_L}.$$

By applying (9) and (10), we can obtain the error functions

$$E_{TFP\_y1}=|W_O \frac{G_{LP}\Delta G_{\text{int}}}{1-G_{LP}(1+\Delta G_{\text{int}})}|$$

$$=|W_O \frac{(e^{-j\omega\tau}-1)[-R_S/(R_L+j\omega L_L)]}{1+[R_S/(R_L+j\omega L_L)]e^{-j\omega\tau}}|$$

and

$$E_{TFP\_y2}=|W_O \frac{\Delta G_{\text{int}}}{1-G_{LP}(1+\Delta G_{\text{int}})}|.$$

$$=|W_O \frac{e^{-j\omega\tau}-1}{1+[R_S/(R_L+j\omega L_L)]e^{-j\omega\tau}}|$$

If we are only interested in system responses below 1000 Hz, the weighting function is defined as:

$W_O(j\omega)=1$ for $\omega < 2\pi$ 1000 rad/sec

$W_O(j\omega) = 0$ for $\omega > 2\pi$ 1000 rad/sec

To study the influence of interface time delay on the simulation accuracy the maximum TFP errors are plotted versus the delay time. **Figure 5** shows that if the simulation error is required to be less than 10%, the maximum time delay allowed is about 15 µs. Evaluation of the error functions over frequency with a 20 µs time delay shows that the maximum values for both functions occur at 1 kHz, where they are cut off by the weighting function (**Figure 6**).

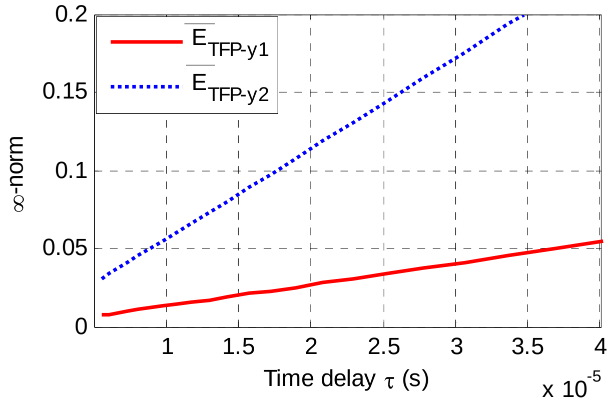


**Figure 5**: Maximum TFP errors versus time delay

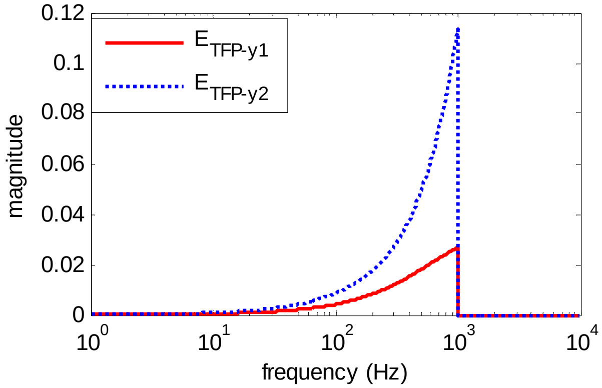


**Figure 6:** TFP errors over frequency domain when the time delay is 20μs

These results are validated through simulations. The entire PHIL system, including the voltage amplification and current feedback, is modeled and simulated in Matlab Simulink. **Figure 7** illustrates the simulation result of the load current ($i_2$) with 1 kHz input signal. As the figure shows, the simulated magnitude of the error current is about 10% of the magnitude of the correct current when a time delay of 20 μs is introduced in the interface,.

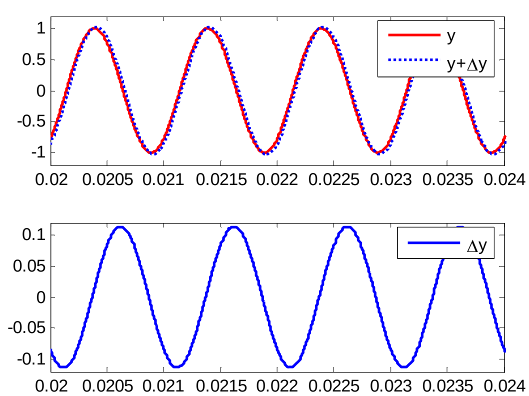


**Figure 7**: Simulation result with a 20 μs time delay

Although the TFP error evaluation is fully based on magnitude comparison, it actually can provide a reasonable measure for the simulation error caused by phase shift. For example, the simulated PHIL load current in **Figure 7** has almost the same magnitude as the correct current. But the TFP error function shows a non-negligible 10% error due to the phase error. This feature is important because in many power system simulation cases the phase shift can result in large errors in quantities such as in real and reactive power.

### 4.2 A NP Type PHIL Accuracy Evaluation Example

The PHIL system in **Figure 3** can also serve as an example for the NP type error examination. We assume this time that the voltage is ideally amplified (without error) while the measured current is subjected to a sensor noise of 50 mA. Due to the large bandwidth of the sensor noise, we treat it as white noise and write:

$$v_0 = 0.05(A)$$

The voltage $v_1$ is the simulation output of interest and we suppose that through the experiment we find its magnitude at 60 Hz is about 1V. Then the input weighting function is approximated by

$$W_I = \frac{|v_0|}{|y|} = 0.05(A/V)\cdot$$

The transfer function from the sensor noise to the output of interest is

$$G_{yv} = \frac{-R_S}{1 + R_S/(R_L + sL_L)}.$$

By applying (16), the NP error at 60 Hz is computed to be 3.35%. The simulation result of $v_1$ in **Figure 8** validates the computation.

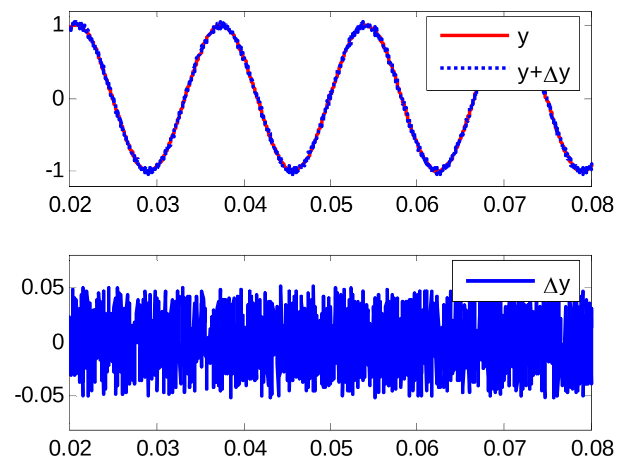


**Figure 8**: Simulation result with current sensor noise

## 5 DISCUSSION

In order to guarantee stability most PHIL systems open loop transfer functions satisfy $|G_{LP}|<1$. This condition can be considered equivalent to the "small gain theorem" in robust-control theory. When the interface perturbation is reasonably small we can approximate

$$|1 + \Delta G_{\text{int}}| \approx 1 \tag{17}$$

and

$$|G_{LP}(1 + \Delta G_{\text{int}})| < 1. \tag{18}$$

Since

$$|1 - G_{LP}(1 + \Delta G_{\text{int}})| \geq 1 - |G_{LP}(1 + \Delta G_{\text{int}})|, \tag{19}$$

(9) and (10) will satisfy

$$E_{TFP\_y1} \leq |W_O| \frac{|G_{LP}| \cdot |\Delta G_{\text{int}}|}{1 - |G_{LP}| \cdot |(1 + \Delta G_{\text{int}})|} \tag{20}$$

and

$$E_{TFP\_y2} \leq |W_O| \frac{|\Delta G_{\text{int}}|}{1 - |G_{LP}| \cdot |(1 + \Delta G_{\text{int}})|}. \tag{21}$$

These two equations provide a method to calculate the upper bound of the TFP error functions, derived using only the magnitude of the system transfer functions. Since obtaining only the magnitude information of a transfer functions is typically easier than deriving the complete expression including the phase information, it is an important advantage of the present method that it can still be utilized as an effective way to estimate simulation accuracy. Most PHIL systems will contain nonlinear elements or “black-box” components for which only approximate information will be available. While based on linear systems theory, the present method can be extended to non-linear systems by utilizing approximations such as the method of equivalent gains. From these gains, the range of the PHIL simulation error can then be estimated from the TFP.

## 6 CONCLUSION

This paper introduces a generalized metric defining the accuracy of PHIL simulations and derives a closed form permitting its computation. This method can provide a quantitative measure to judge the accuracy and hence reliability of a PHIL simulation result performed on an existing test bed. It can also be used to design suitable interfaces for achieving a desired accuracy in new installations.

## 7 REFERENCES


[1] E. Acha, O. Anaya-Lara, J. Parle, M. Madrigal, “Real-Time Simulator for Power Quality Disturbance Applications,” *Proceedings .on Ninth International Conference*, vol. 3, 1-4 Oct. 2000

[2] W. Zhu, S. Pekarek, J. Jatskevich, O. Wasynczuk, D. Delisle, “A Model-in-the-Loop Interface to Emulate Source Dynamics in a Zonal DC Distribution System,” *IEEE Transactions on Power Electronics,* vol. 20, Issue 2, Mar 2005

[3] Slater, H.J.; Atkinson, D.J.; Jack, A.G, “Real-time emulation for power equipment development. II. The virtual machine,” *IEE Proceedings*, vol. 145, Issue 3, May 1998

[4] Wu, X.; Lentijo, S.; Deshmuk, A.; Monti, A.; Ponci, F.; “Design and implementation of a power-hardware-in-the-loop interface: a nonlinear load case study,” *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005*, vol. 2, March 2005

[5] W. Ren, M. Steurer, T. L. Baldwin, “Improve the Stability and Accuracy of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithms,” *IEEE Industrial and Commercial Power Systems Technical Conference*, Edmonton, ALB Canada, May 6-10, 2007.

[6] M. Bacic, “On hardware-in-the-loop simulation,” *Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference 2005,* Seville, Spain, December 12-15, 2005

[7] S. Ayasun, S. Vallieu, R. Fishl, and T. Chmielewski, “Electric machinery diagnostic/testing system and power hardware-in-the-loop studies," *Proc. 4th IEEE Int. Symp. Diagnostics Electric Machines, Power Electronics Drives*, Atlanta, GA, Aug. 24–26, 2003