Experimental Studies and Modeling of an Information Embedded Power System

S. P. Carullo and C. O. Nwankpa
Drexel University
Philadelphia, Pennsylvania, USA
carullo@cbis.ece.drexel.edu, chika@nwankpa.ece.drexel.edu

Abstract

This paper develops a model of an electrical power system, with its inherent embedded communication system, for the purpose of studying the characteristics of power system measurement errors due to communication delays. This model is referred to as an "information embedded power system" to emphasize the inclusion of information variables that represent measurements that have been delivered across the communication system and observed at a control center. These information variables are added to the standard power system model for the energy balance within the power system. A stochastic system model is developed, which is composed of both the physical infrastructure of the power system as well as the embedded computer network communication infrastructure. This type of analysis is an extension of traditional observability approaches, which usually only assume steady-state conditions in the power system and do not consider time delays in delivering measurements. An experimental platform has also been designed to validate the developed model.

1. Introduction

An information embedded power system is an extension of traditional power systems with added monitoring, control, and telecommunication capabilities. A simplified illustration of an information embedded power system is shown in Figure 1 below. This system consists of: i) power system hardware (shown as a three-bus system diagram); ii) the measurement system (represented by three remote terminal computers - RTUs); iii) the communication system; and iv) the electric utility control center. In this system, the RTU computers record power system measurements and send them in real-time over a computer network to the power control center. Control centers are also capable of sending messages back to the RTUs to perform control actions such as opening/closing breakers, transformer tap changing, generation control, etc. This paper is concerned with how the random characteristics of the computer network can affect the accuracy of the measurements sent from the RTUs to the control center. Large amounts of computer network traffic may result in large measurement errors and temporarily render parts of the power system unobservable.

The purpose of traditional power system observability methods, such as [1-4], are used to determine whether the states of a power system are measurable. If a power system is found to be observable, state estimation algorithms [5-13] can then be run to calculate the unmeasured states of the system. Currently, these methods are widely used in power system control and monitoring centers. These methods assume steady state operating conditions in a power system and do not consider measurement errors due to delays in delivering the measurements. In other words, traditional power system monitoring methods assume that the state of the power system remains unchanged during the time it takes to deliver a newly recorded set of measurements to a control center.

This paper is a first step in attempting to characterize measurement errors that result from random delays in delivering the measurements. This paper refers to these types of errors as "Measurement Delay Errors" (or MDEs). It will be important to consider MDEs when implementing modern control functions within an energy control center, which may require more accurate real-time power system models on a finer time scale.

An experimental platform was designed at Drexel University's Center for Electric Power Engineering in order to experimentally measure and characterize measurement delays in a scaled down version of an information embedded power system. The experimental platform will not be discussed in detail in this paper, but more information about the experimental setup can be found in [14].

A system model has also been developed to quantify MDEs that result when power systems utilize an Ethernet network communication infrastructure to send measurements to a central energy control center. This model will illustrate how computer network traffic can affect the magnitude of MDEs. The magnitude of MDEs will also be shown to depend on power system loading and dynamics. The experimental platform is used to validate the developed model.

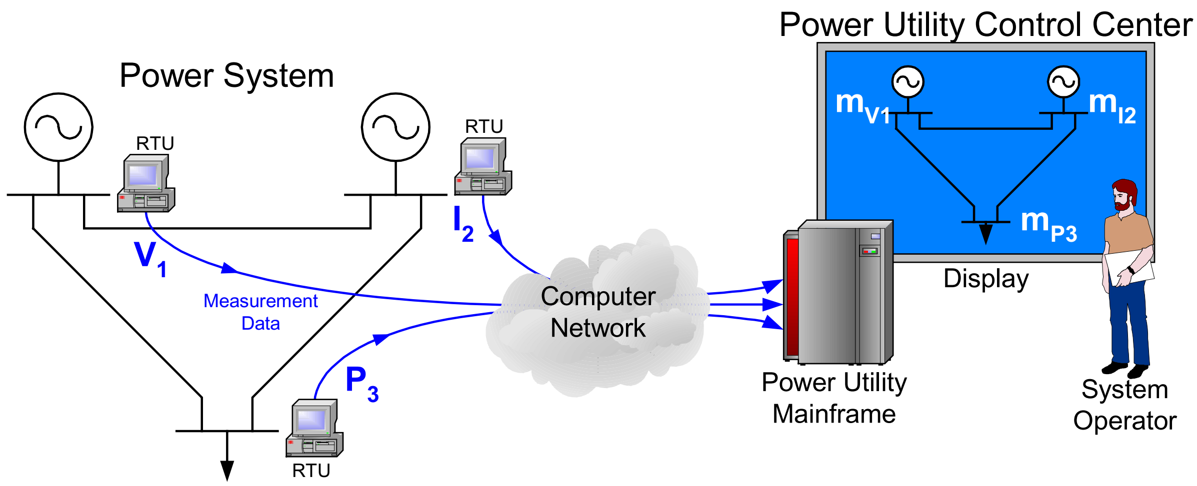

Figure 1. Illustration of an Information Embedded Power System

The following section presents the background and motivation for studying information embedded power systems. Section 3 develops a preliminary stochastic model to quantify measurement delay errors. Section 4 presents experimental and simulation results when measuring delay errors on a sample three-bus power system (under various power system and computer network loading conditions). Finally, the conclusion of the paper is presented in Section 5.

2. Background

Modern SCADA systems typically consist of Remote Terminal Unit (RTU) computers, which record real-time measurements and deliver this data over a communication system to a control center. There are two main categories of real-time measurements: (i) analog measurements, which include bus voltages, real and reactive power injections, and real and reactive power flows and (ii) status measurements consisting of switch and breaker positions. Analog data usually originate from transducers. Status data may come from switches, breaker contacts, or other electronic devices.

There has been much effort over the last decade towards the standardization of communication protocols used in SCADA systems by electric power utilities. The motivation for this standardization is to ease the integration process for inter-company data sharing. In 1990, the Electric Power Research Institute (EPRI) began development of a concept known as the Utility Communication Architecture (UCA). The main purpose of the UCA was to identify a suite of existing communication protocols that could be easily mixed and matched, provide the foundation for the functionality required to solve the utility enterprise communication issues, and be extensible for the future [15]. The UCA came up with a solution that involved using Ethernet over twisted pair or fiber for the data link/physical layer of the computer network. Ethernet was selected due mainly to its dominance in the marketplace, high availability, scalability, and low cost hardware (such as hubs, bridges, and routers).

These modern trends, towards implementing computer networks for transmitting power system measurements to the power system control center, have provided a motivation for studying the effect of network traffic on the accuracy of power system measurements. Up until now, little research has been performed to analyze how measurement delays (due to computer network traffic) can affect the accuracy of power system measurements. Also, little efforts have been made to show how power system loading and dynamics can further impact the magnitude of these errors.

3. Analytical Issues

Measurements obtained from our experimental platform will be used for the purposes of first quantifying parameters that are inherent in the assumed model of the power system and secondly, for eventual model validation. The model of our system will be composed of both the physical infrastructure of the power system as well as the information infrastructure (computer network). Traditionally, the following model depicted the power system behavior:

$$\begin{aligned} \dot{\mathbf{x}} &= f(\mathbf{x},\mathbf{y}) \\ 0 &= g(\mathbf{x},\mathbf{y}) \end{aligned} \tag{1}$$

where **x** represented the dynamic states of the system (like generator angles and velocities) and **y** represented the algebraic states (like load bus voltage magnitudes and phases). In many cases, this system of differential algebraic equations is reduced to a system of ordinary differential equations under the assumption that all algebraic variables are always implicitly expressed as functions of dynamic variables to obtain:

$$\dot{\mathbf{x}} = f(\mathbf{x}) \tag{2}$$

In the past, when considering uncertain perturbations in the system, such as load fluctuations, this equation was transformed to a stochastic differential equation:

$$\dot{\mathbf{x}}_\varepsilon = f(\mathbf{x}_\varepsilon) \tag{3}$$

where $\mathbf{x}_\varepsilon$ refers to the stochastically perturbed state of the system transformed as such through the inclusion of additive zero mean gaussian noises. These noises were basically quantified though both the variances of load fluctuations and measurement errors. In our case, since the focus is mainly on measurement delay errors, these noises will be quantified through the variance of affected voltages, currents, and power measured at remote points in the information network. It is the measure of these variances among others that serve as the motivation for the experimental setup.

The following subsections discuss the unperturbed and perturbed system models that are used to describe the physical infrastructure of the power system and the information infrastructure. Equations (2) and (3) are formulated to include not only states of the system such as generator angles and velocities, but also "information variables", which include the bus voltages, currents, and power injection measurements viewed remotely at the energy control center. "Measurement" or "Information" variables will always be a delayed version of actual variables due to the random time delays in delivering measurements to the energy control center over a computer network.

3.1. Unperturbed System Model

This paper builds upon the classical dynamic model of an n-bus and m-machine power system. The classical model is expanded to represent both the physical infrastructure of the power system as well as the information infrastructure. Additional dynamic state variables are added to the classical model in order to describe the "information variables" or "measurement variables", which are the delayed versions of certain power system variables seen at the control center. These information state variables include the voltage, current, and power at each bus in the power system. The complete n-bus, m-machine system is thus described by:

$$\begin{aligned} &\dot{\delta}_i = \omega_i \\ &\dot{\omega}_i = -\frac{D_i}{M_i}\omega_i + \frac{1}{M_i}\left[P_{mi} - P_{ei}(V,\delta)\right] \qquad i = 2,\ldots,m \\ &\dot{m}_{Vk} = \frac{1}{r_k}\left(V_k - m_{Vk}\right) \qquad k = 1,\ldots,n \\ &\dot{m}_{Ik} = \frac{1}{r_k}\left(I_k - m_{Ik}\right) \\ &\dot{m}_{Pk} = \frac{1}{r_k}\left(P_{lk} - m_{Pk}\right) \end{aligned} \tag{4}$$

where:

$$P_{ei}(V,\delta) = |V_i|^2 |Y_{ii}| \cos\theta_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{5}$$

The following notation is used for the power system variables and parameters:

δ_i	phase angle
ω_i	frequency
M_i	inertia coefficient
D_i	damping coefficient
P_{li}	bus real power injection
$P_{mi}(P_{ei})$	mechanical input (electrical output) power
V_i	bus voltage
I_i	bus current injection
E_i	internal generator voltage
$\lvert Y_{ij}\rvert(\theta_{ij})$	magnitude (phase) of ijth element of Ybus

The following notation is used for the "information" or "observed" variables:

m_{vk}	bus voltage measurement
m_{Ik}	bus current measurement
m_{Pk}	bus power injection measurement
r_k	computer network time constant

M_i, E_i, and P_{mi} are assumed to be constant throughout all transients. All loads are modeled as constant power loads. Bus 1 is taken as the swing bus. It is assumed that the information variables can be scaled to per unit values as in traditional power system models. The state vector in terms of equation (2) is:

$$\mathbf{x} = \begin{bmatrix} \delta \\ \omega \\ m_V \\ m_I \\ m_P \end{bmatrix} \tag{6}$$

In this approach, we are assuming that a first-order linear differential equation can be used to solve for the information variables for a given set of power system variables (bus voltage, bus current injection, or bus power injection). To clarify this issue, consider the following real world scenario:

A remote terminal unit (RTU) computer is monitoring and recording the voltage at a certain bus in a power system. The RTU is made to send bus voltage measurement packets over an Ethernet computer network to an energy control center at a regular time interval t. As the energy control center computer (or master station) receives these measurements, they are displayed on a monitor. Suddenly, the true bus voltage that is being monitored jumps instantaneously from 0.8 Vp.u. to a new voltage value of 1.0 Vp.u.

In this scenario, we do not expect the observed voltage value being displayed in the control center to instantly change to this new voltage value. The observed voltage will have a delayed response due to the time delays in delivering the voltage measurements. It is assumed that in the absence of external network traffic (or noise) and as the measurement time interval t approaches zero, the observed voltage will exponentially approach the new true voltage. This exponential time constant is selected as the mean time delay in delivering the true voltage value to the energy control center. Figure 2 shows the step response for the observed bus voltage with a time constant $r = 0.05$ seconds. This time constant can be experimentally determined for a given computer on local area network by determining the mean measurement delay.

In reality, we know that the observed voltage will not approach the new voltage value in a pure exponential fashion for the above scenario. Instead, the observed voltage value will quickly change to the new true value after the transmission delay (or time constant value), as shown by the red curve in Figure 2. This first order approximation allows ease in analysis and will be sufficient for a first modeling attempt. It is assumed that the measurement time delay will be the same for all observed variables at a given bus, since it is assumed these variables will be grouped together in the same measurement packet. The value of r_k will be the same for all power system buses ($r_k = r$ for $k = 1$ to n) since all RTUs are on a single LAN and therefore share the same collision domain.

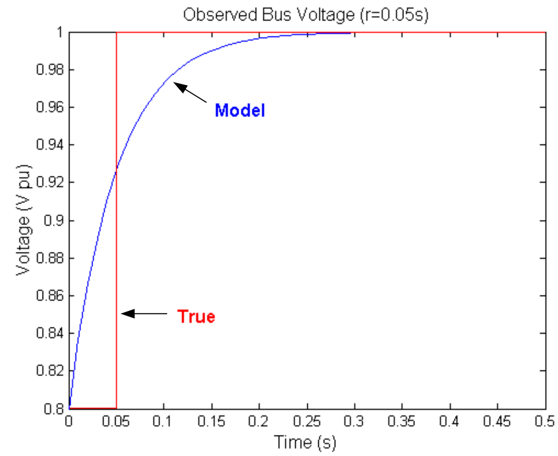

Figure 2. Step Response of Observed Voltage for Example Scenario

3.2. Perturbed System Model

The differential equations for the observed voltages, currents, and power injections shown in equation (4), are assumed to be only valid if the computer network has a first order response with a fixed time constant and there is no random component of the delay in sending measurement packets over the computer network. Normally, there will be random amounts of background traffic present on the computer network due to other computer conversations taking place on the network. This background traffic can cause collisions and queuing (buffering) delays that will result in random delays in delivering measurement packets to the energy control center. Therefore, in reality there will be a random component to the time constant r_k of the computer network. In this model, we will assume that there will be a zero mean gaussian noise additive component to the time constant r_k. We introduce a new variable s_k, that is simply the inverse of the time constant r_k:

$$s_k = \frac{1}{r_k} \tag{7}$$

We next add a fluctuating component to s_k:

$$s_k \to s_k\left[1 + \gamma_k \dot{w}(t)\right] \tag{8}$$

where $\dot{w}(t)$ is a Gaussian white noise and γ_k is a scaling parameter describing noise intensity [16] at the kth bus. The parameter γ_k is the ratio of the respective standard deviation to its corresponding mean value of s_k. The parameter γ_k will vary depending on the level of background traffic (noise) at each monitored bus. This paper quantifies network background traffic as the average percentage of computer network bandwidth utilization. Since this paper assumes that all RTU computers monitoring the power system are connected to the same computer LAN, the background traffic will be the same at all monitored buses in the power system. This means that the value of γ_k will be equal for all values of *k*. The model presented in this paper can also be used for larger switched networks with many separate collision domains, where the value of γ_k will not be equal for all buses.

Substituting (8) into the observed variable equations in (4), we obtain the following stochastic differential equations [17]:

$$\begin{aligned} \dot{m}_{Vk} &= s_k(V_k - m_{Vk}) + s_k\gamma_k(V_k - m_{Vk})\dot{w}_{Vk} \\ \dot{m}_{Ik} &= s_k(I_k - m_{Ik}) + s_k\gamma_k(I_k - m_{Ik})\dot{w}_{Ik} \\ \dot{m}_{Pk} &= s_k(P_{lk} - m_{Pk}) + s_k\gamma_k(P_{lk} - m_{Pk})\dot{w}_{Pk} \end{aligned} \quad k = 1,\dots,n \quad (9)$$

Next let:

$$\sqrt{\varepsilon_l} = \inf\left\{\frac{s_k\gamma_k}{\sqrt{2\beta}}\right\} \qquad k = 1,\dots,n \qquad (10)$$

and

$$\sqrt{\varepsilon_k} = \frac{s_k\gamma_k}{\sqrt{2\beta\varepsilon_l}} \qquad k = 1,\dots,n \qquad (11)$$

Then the noise terms applied to the computer network time constant for the observed voltage, current, and power injections respectively (at the k[th] bus) are given as:

$$\sqrt{2\beta\varepsilon_l\varepsilon_k} \qquad (12)$$

In this approach, β is used to rescale the intensity of the noises for mathematical convenience. The corresponding equations representing the dynamics of the system, after substituting (12) into (4), will be as follows:

$$\begin{aligned} \dot{\delta}_i &= \omega_i \\ \dot{\omega}_i &= -\frac{D_i}{M_i}\omega_i + \frac{1}{M_i}[P_{mi} - P_{ei}(V,\delta)] \qquad i = 2,\dots,m \quad k = 1,\dots,n \qquad (13) \\ \dot{m}_{\varepsilon Vk} &= \frac{1}{r_k}(V_k - m_{\varepsilon Vk}) + \sqrt{2\beta\varepsilon_l\varepsilon_k}(V_k - m_{\varepsilon Vk})\dot{w}_{Vk} \\ \dot{m}_{\varepsilon Ik} &= \frac{1}{r_k}(I_k - m_{\varepsilon Ik}) + \sqrt{2\beta\varepsilon_l\varepsilon_k}(I_k - m_{\varepsilon Ik})\dot{w}_{Ik} \\ \dot{m}_{\varepsilon Pk} &= \frac{1}{r_k}(P_{lk} - m_{\varepsilon Pk}) + \sqrt{2\beta\varepsilon_l\varepsilon_k}(P_{lk} - m_{\varepsilon Pk})\dot{w}_{Pk} \end{aligned}$$

Therefore, the perturbed state vector in terms of equation (3) is:

$$\mathbf{x}_\varepsilon = \begin{bmatrix} \delta \\ \omega \\ m_{\varepsilon V} \\ m_{\varepsilon I} \\ m_{\varepsilon P} \end{bmatrix} \qquad (14)$$

where $m_{\varepsilon V}$, $m_{\varepsilon I}$, and $m_{\varepsilon P}$ are the perturbed versions of m_V, m_I, and m_P, respectively. Thus, $\mathbf{x}_\varepsilon$ is the perturbed state vector.

The goal of the experimental setup was to obtain the parameters s_k and γ_k. The parameter s_k is obtained by experimentally measuring the mean delay time in sending a measurement from the k[th] bus to the energy control center with no external noise (or traffic) present on the network. This is under the assumption that the distribution of noise around s_k is ergodic. The parameter γ_k is found as the ratio of the standard deviation to the mean value of the delay time for sending measurements from the k[th] bus to the energy control center. The measurements for the γ_k parameters must be found for different levels of background network traffic because this parameter will vary with traffic intensity. For example, in order to simulate $m_{\varepsilon V}$ for a specific level of background network utilization in equation (13), the γ_k parameters must be experimentally found for that level of traffic intensity.

4. Experimental and Simulation Results

The stochastic model that was developed in the previous section was tested on the IEEE three-bus system (shown in Figure 3). The system parameters for the IEEE three-bus system are shown in Table 1. For the simulation scenario, it is assumed that an RTU computer is monitoring the bus-3 voltage and sending measurement packets across an Ethernet network to the control center. The developed model is used to simulate the bus-3 voltage observed at a control center, during a 100 second power system transient. The observed waveforms will have errors due to the delays in delivering the measurements.

In order to obtain the true bus-3 voltage during a transient, the IEEE 3-bus system was simulated using the Voltage Stability Toolbox for Matlab (VST) [18], which was developed at Drexel University. Among the capabilities of the VST toolbox, it can be used for performing time-domain simulations of the classical dynamic power system model that was presented in (4). For the simulation, the generator-2 phase angle was perturbed from its steady state value of -0.1048 radians to a value of 0.4 radians. The resulting bus-3 voltage transient was captured over a period of 100 seconds. This voltage transient is shown in Figure 4. This voltage transient represents the true voltage at bus-3 (V_3) without any measurement delay errors. The developed information model (13) is used to predict the observed version of the bus-3 voltage (m_{V3}) at the control center, under different levels of background network traffic.

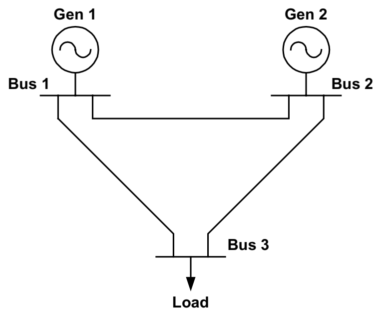

Figure 3. IEEE 3-Bus System

Table 1. System Parameters for IEEE 3-Bus System

Bus Data					Line Data	
Bus #	P	Q	M	D		
Bus 1	---	---	1.0	1.5	R_{12}	0.01938
					X_{12}	0.05917
Bus 2	0.183	0.297	1.0	1.5	R_{23}	0.04699
					X_{23}	0.19800
Bus 3	-0.942	0.044	---	---	R_{31}	0.05403
					X_{31}	0.22300

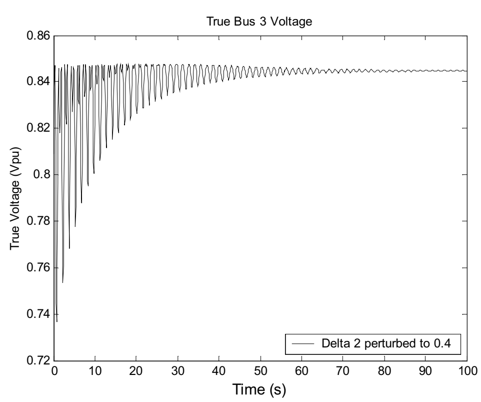

Figure 4. Simulated Bus-3 Voltage Transient from IEEE 3-Bus System

For the experimental validation of the model, the voltage transient was loaded into a RTU computer and sent in real time over the Ethernet network to the control center. Both the simulations and the experiments were repeated for several levels of background network traffic.

4.1. Experimental Results

In order to experimentally measure the delay errors, the true voltage transient data (shown in Figure 4) was loaded into a RTU computer and sent in real-time over the Ethernet network to the control center at fixed time steps for the 100 second data duration. The experiments were repeated using both the UDP and TCP transport protocols and for different levels of background network utilization. A time step of 200ms was used for the TCP transport protocol and a time step of 20ms was used for the UDP. The bus-3 voltage value interpolated at each time step, t_i, was packaged into a single IP packet before being sent over the network. During each experimental trial, the delays were measured for each measurement packet and the observed voltage waveform at the control center was constructed (incorporating the measured delays).

The experimental results in the figures that follow show the observed bus-3 voltages at the control center and the corresponding measurement delay errors. Results are shown for the TCP transport protocol with different levels of Ethernet utilization. Figures 5-7 show results using the TCP transport protocol for 10%, 40%, and 80% Ethernet utilization levels, respectively.

In the figures below, the measurement delay errors are shown to increase with increasing network traffic noise. These errors are magnified during transients, when measured values are changing more rapidly. The measurement delay errors are much smaller when using the UDP transport protocol. This is because of there is a large overhead when using TCP, due to the handshaking and flow control algorithms. This overhead causes a much larger delay then in the case of UDP.

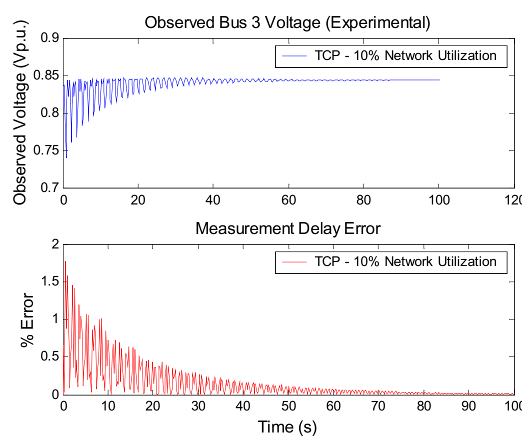

Figure 5. Observed Bus-3 Voltage with 10% Network Utilization using TCP - Experimental

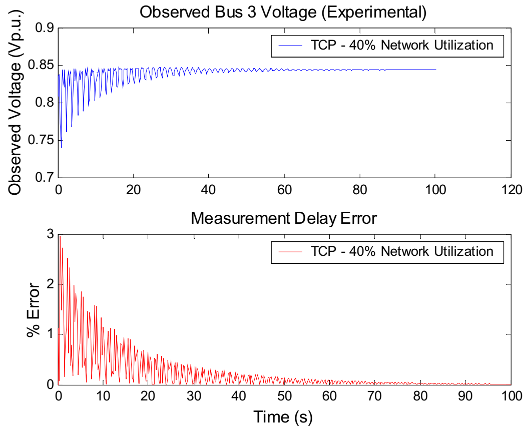

Figure 6. Observed Bus-3 Voltage with 40% Network Utilization using TCP - Experimental

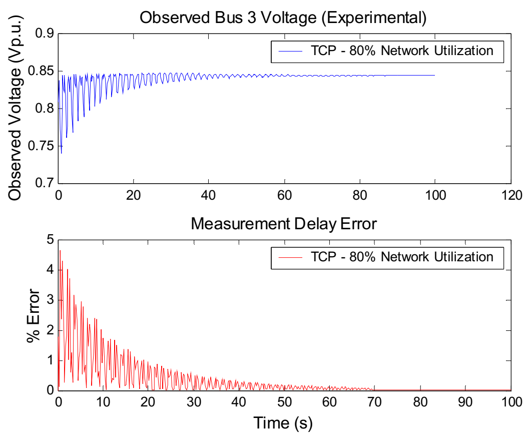

Figure 7. Observed Bus-3 Voltage with 80% Network Utilization using TCP - Experimental

4.2. Simulation Results

Figure 8 shows the general simulation procedure for solving the stochastic differential equations in the developed information model. As mentioned above, the IEEE three-bus system is first simulated using the VST toolbox for Matlab. The VST toolbox thus solves the δ and ω differential equations in the previously described model. This can be done since the δ and ω equations are decoupled from the information variable equations in the model (see 13). The VST time domain simulation results provide the true voltage, current, and power injection data from the power system. The output variables from this time domain simulation are then imported into a fifth-order Runge-Kutta ODE solver, which is part of the Numerical Recipes in C software package [19]. The Runge-Kutta program is modified to solve the information variable stochastic differential equations, utilizing the imported VST data in the solution process. The solutions are obtained by performing a Monte Carlo simulation, which involves solving the differential equations 1000 times, using a single gaussian distributed value for the appropriate time constant parameter during each iteration. The final solution is taken as the average of resulting 1000 solution waveforms. The white noise sequences are generated using Simulink and are imported into the Runge-Kutta ODE solver. Samples from the noise sequences are taken successively for each iteration of the Monte Carlo simulation. The noise sequences are generated with the desired mean, variance, and sample time that is required for the particular simulation being run, and will be dependent on the model parameters. For example, if it were desired to predict the information variables at the control center when using the TCP transport protocol with 40% network utilization on the network, one would use a Gaussian distributed noise array with a mean of 0.110s and variance of 4.20e-3s.

The model is used to predict the observed version of the bus-3 voltage (m_{V3}) at the control center during the 100 second transient shown in Figure 4. Solutions were found using both the TCP and UDP transport protocols with background traffic levels of 10%, 40%, and 80% network utilization. The solutions that result when using the TCP protocol are shown in Figures 9-11. The error between the simulated observed voltage waveform and the experimentally obtained waveforms are also presented in each of the figures. It can be seen that the simulation results closely match the experimentally obtained waveforms obtained for a given network utilization. It can also be seen the model loses some accuracy at higher network utilizations.

5. Conclusion

This paper examined how communication delays in delivering power system measurements across a computer control network can affect the accuracy of these measurements as viewed by remote hosts on the network. A stochastic model was developed, which was composed of both the physical infrastructure of the power system as well as the embedded network communication infrastructure. This model included new "information" state variables that represent power system measurements observed at a remote point in the computer network. This model is the first step in examining measurement errors that result from the combined effect of delays in delivering power system measurements and power system dynamics.

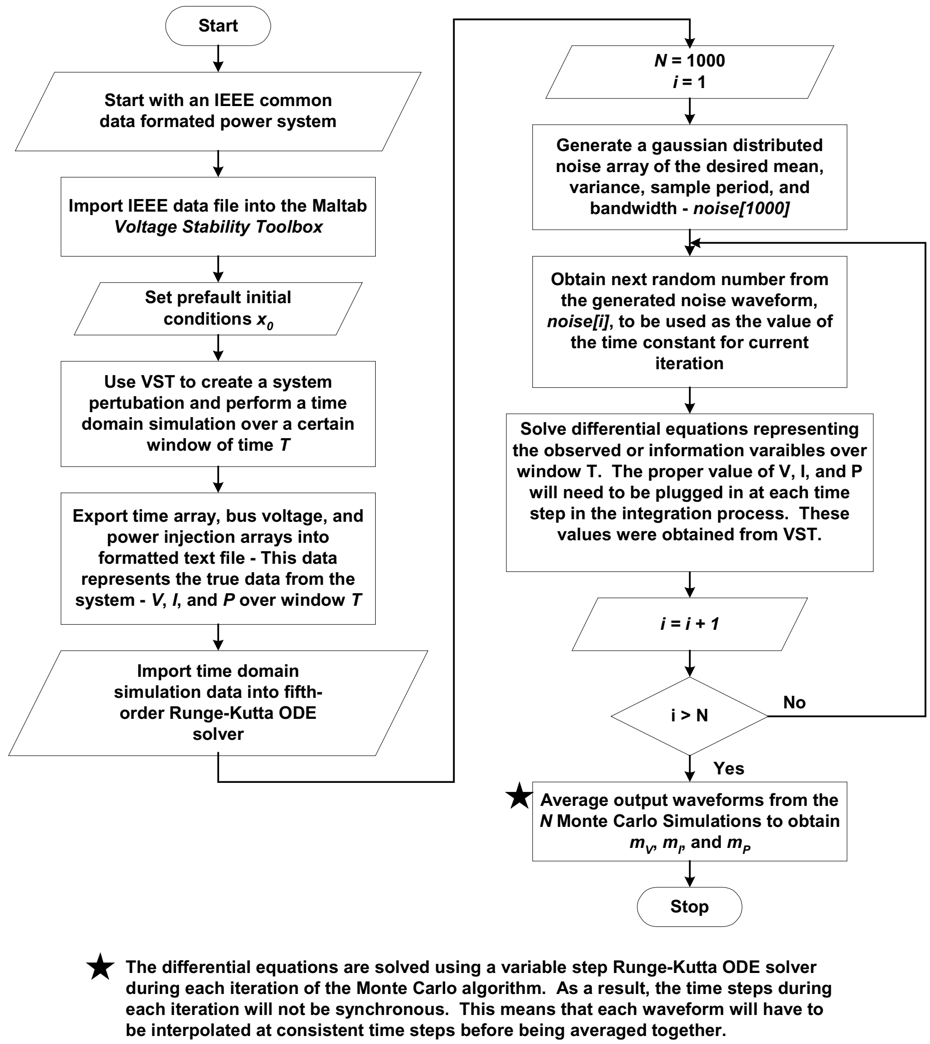

Figure 8. The Simulation Procedure for Solving the Information Variable Stochastic Differential Equations

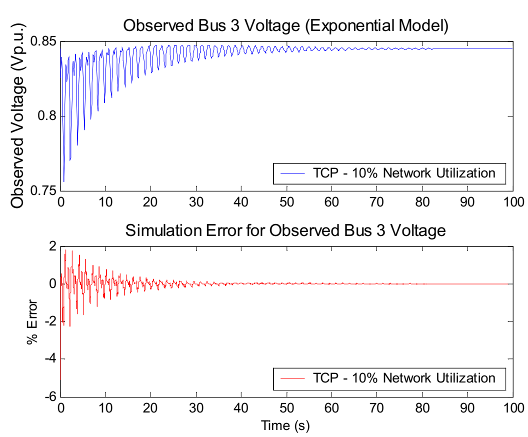

Figure 9. Observed Bus-3 Voltage with 10% Network Utilization – Simulated

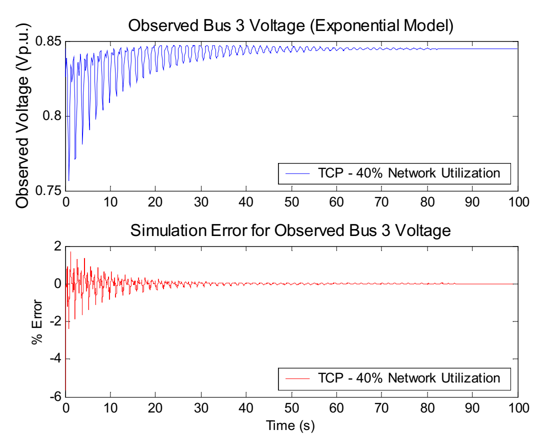

Figure 10. Observed Bus-3 Voltage with 40% Network Utilization using TCP - Simulated

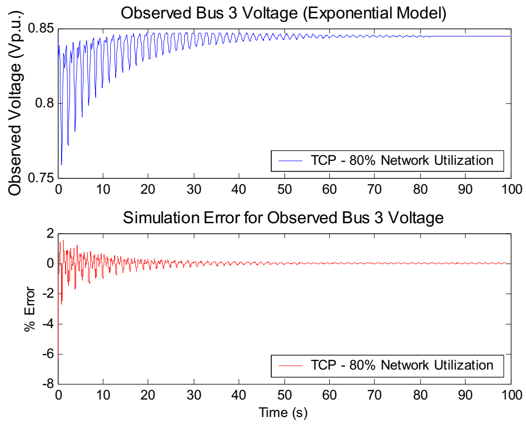

Figure 11. Observed Bus-3 Voltage with 80% Network Utilization using TCP - Simulated

It was experimentally shown that MDEs increase with increasing network traffic. It was also shown that these errors are magnified during power system transient behavior. These results show the weaknesses present in traditional observability approaches, which usually only assume steady-state conditions in the power system and do not consider time delays in delivering measurements. By acknowledging the coupling that exists between the communication system and the power system, more accurate models can be developed that reflect the true complexities in modern power systems.

6. References

[1] K. A. Clements and B. F. Wollenburg, "An Algorithm for Observability Determination in Power System State Estimation", Paper No. A75-447-3, *Presented at IEEE PES Summer Meeting*, July 1975.

[2] G. R. Krumpholz, K. A. Clements, and P. W. Davis, "Power System Observability: A Practical Algorithm Using Network Topology", *IEEE Transactions on Power Systems*, Vol. PAS-99, July 1980, pp. 1534-1542.

[3] T. H. VanCutsem, "Power System Observability and Related Functions – Deviation of Appropriate Strategies and Algorithms", *Electrical Power and Energy Systems*, Vol. 7, July 1985, pp. 175-187.

[4] A. Monticelli and F. F. Wu, "Network Observability: Theory", *IEEE Transactions on Power Systems*, Vol. PAS-104, No. 5, May 1985, pp. 1042-1048.

[5] F. C. Schweppe, J. Wildes, and D. Rom, "Power System Static State Estimation", *Power System Engineer Group*, MIT Rep. 10, November 1968.

[6] F. C. Schweppe, et. al., "Power System Static State Estimation: Part I-III", *IEEE Transactions on Power Systems*, Vol. PAS-89, January 1970, pp. 120-135.

[7] F. C. Schweppe and E. J. Handschin, "Static State Estimation in Electric Power Systems", *Proceedings of the IEEE*, Vol. 62, July 1974, pp. 972-983.

[8] A. Monticelli and F. F. Wu, "Observability Analysis for Orthogonal Transformation Based State Estimation", *IEEE Transactions on Power Systems*, Vol. PWRS-1, February 1986, pp. 201-208

[9] A. Simoes-Costa and V. H. Quintana, "A Robust Numerical Technique for Power System State Estimation", *IEEE Transactions on Power Systems*, Vol. PAS-100, February 1981, pp. 691-698.

[10] J. W. Gu, K. A. Clements, G. R. Krumpholz, and P. W. Davis, "The Solution of Ill-Conditioned Power System State Estimation Problems via the Method of Peters and Wilkinson", *PICA Conference Proceedings*, 1983, pp. 239-246.

[11] J. W. Wang and V. H. Quintana, "A Decoupled Orthogonal Row Processing Algorithm for Power State Estimation", *IEEE Transactions on Power Systems*, Vol. PAS, August 1984, pp. 2337-2344.

[12] A. Monticelli, "Electric Power System State Estimation", *Proceedings of the IEEE*, Vol. 88, No. 2, February 2000, pp. 262-282.

[13] A. Monticelli, *State Estimation in Electric Power Systems, A Generalized Approach*, Kluwer Academic Publishers, Boston, MA, 1999.

[14] S. Carullo and C.O. Nwankpa, "Analysis of Measurement Delay Errors in an Ethernet Based Communication Infrastructure for Power Systems", *IEEE International Symposium on Circuits and Systems*, May 2002, Scottsdale, Arizona.

[15] M. Adamiak and W. Premerlani, "The Role of Utility Communications in a Deregulated Environment", *Proceedings of the 32nd Hawaii International Conference on System Sciences*, 1999.

[16] H. Mohammed and C.O. Nwankpa, "Stochastic analysis and simulation of grid-connected wind energy conversion system", *IEEE Transactions on Energy Conversion*, Vol. 15, No. 1, March 2000, pp. 85–90.

[17] Z. Schuss, *Theory and Applications of Stochastic Differential Equations*, New York, NY, J. Wiley & Sons, 1980.

[18] S. Ayasun, C. O. Nwankpa, and Harry G. Kwatny, "Bifurcation and Singularity Analysis with Voltage Stability Toolbox", *Proc. of the 31st North American Power Symposium*, pp. 390-397, San Obispo, CA, October 1999.

[19] W. H. Press, S A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes in C: The Art of Scientific Computing*, Cambridge University Press, 2nd edition, 1993.