2013 IREP Symposium-Bulk Power System Dynamics and Control –IX (IREP), August 25-30, 2013, Rethymnon, Greece

Integration & Automation: From Protection to Advanced Energy Management Systems

Sakis Meliopoulos, G. J. Cokkinides,
S. Grijalva, R. Huang, E. Polymeneas
School of Electrical and Computer Engineering
Georgia Institute of Technology

Paul Myrda, Evangelos Farantatos, EPRI
Mel Gehrs, Gehrs Consulting, Inc.

Abstract

This paper proposes an integrated and seamless infrastructure for protection, control and operation of an electric power system. At the lower level we propose a on dynamic state estimation of a protection zone for the purpose of providing protection for the zone. This scheme simplifies the protection approach for the zone by not requiring coordination with other protection zones (setting-less protection). The scheme provides the real time dynamic model of the zone as well as the real time operating conditions. The scheme can be also implemented in present day numerical relays with GPS synchronization. Using this basic protection infrastructure, we propose that the real time model of substation be autonomously created, send to the control center where the real time model of the system is also autonomously created. The system wide real time model is used to perform system optimization functions, and then send commands back through the same communication structure to specific power system components. Since protection is present in any power apparatus the proposed approach is realizable with very small investment. The availability of the real time dynamic state of the system enables the seamless integration of applications in the proposed system. Three applications are discussed in the paper: (a) setting-less protection, (b) stability monitoring, and (c) voltage/var control.

Introduction

The changing face of the electric power system due to new power apparatus and the proliferation of customer owned resources and smart devices calls for new approaches for protection, control and operation of the emerging electric power system. The emerging system requires better protection, more integration and more automation. Better protection is required as we deal with systems with power electronic interfaces that limit fault currents to levels comparable to load currents [1-2]; a fact that makes the traditional protection approaches obsolete. On the other hand, the traditional Energy Management System (EMS) provides decision support by monitoring and controlling the electric system based on traditional SCADA systems. However, integrating additional functions into this kind of EMS is far from simple [3]. According to [4], EMSs fail to offer the scalability, functionality, and operational capabilities required for managing the large number of distributed and demand-side resources that do not conform to the distributed trend characteristic of modern electric power systems. Moreover, most EMSs are inflexible in facilitating variations in the system infrastructure or changes in objectives. In other words, each EMS uses task-specific, piece-meal models and applications that remain largely incompatible and non-interoperable and is designed to be applied only on the corresponding systems for which it was originally designed. Decision-making in the future grid requires novel frameworks that break down historical barriers and that enable diverse, interrelated and complex information sources and systems to interoperate, achieving seamless engineering and advanced analytics capabilities on an enterprise-wide basis. The availability of massive measurement data coming from Intelligent Electronic Devices (IED), advances in high-performance computing, modern software architectures, and innovative common models and unified application propositions, have the potential to achieve seamless decision-making, enabling utilities to achieve unprecedented agility and effectiveness.

The main objective of this paper is to propose an infrastructure of data acquisition systems that provide the necessary information for an automated EMS system that enables autonomous distributed state estimation, model validation, simplified protection, and an integrated system that supports all necessary applications. The seamless integration of applications enables the system to take advantage of available utility and customer resources to increase system efficiency (loss minimization, load

978-1-4799-0199-9/13/$31.00 ©2013 IEEE

levelization, etc.) and to dramatically improve system reliability.

Proposed Approach

The overall proposed structure is shown in Fig. 1. The system starts from the relays that monitor power apparatus (a protection zone) and performs dynamic state estimation at the apparatus level. The dynamic state estimation is performed a few thousand times per second depending on the sampling period of the data acquisition systems. For example, if the relay samples 4000 times per second, the dynamic state estimation is executed 2000 times per second (it uses two successive sampled data, sees dynamic state estimation). This process is described in the section setting-less protection and it has been demonstrated with extensive numerical experiments and in the laboratory. The indicated relay is a numerical relay on which a number of new functions have been added. We will refer to this relay as Universal Monitoring Protection and Control Unit (UMPCU). The UMPCU provides the real time model of the component, estimated measurements and status of connectivity of the component at very fast speeds. These results are used to perform component protection (setting-less protection) [5]. The results of the dynamic state estimation over a period of one cycle are used to compute the state of the component in the "phasor domain", see block "Conversion to Phasor Model". These results include the following information for the power apparatus (protection zone): ((1) connectivity, (2) device model, (3) measurements/data, (4) controls and (5) operating limits). A simplified example conversion of time domain model to phasor domain model is shown in Figure 2. Subsequently, this information is used to synthesize the substation state as shown in Fig. 1. Note that the substation state is updated once per cycle. Finally the substation state is transmitted to the control center where the system state is synthesized, see Figure 3. Note that the synthesis of the substation state as well as the synthesis of the system state at the control center, does not require additional computations since the component models are all in UTC time (due to the GPS synchronized measurements) and therefore they can be simply merged to provide the system wide model.

It should be stressed that the functional specifications of the UMPCU can be met by current top-of-the-line numerical protective relays. Specifically, the computational power of these relays is adequate to perform the analytics of the UMPCU, i.e. the state estimation based protection function and the extraction of the real time model of the component by appropriate programming. The UMPCUs are also able to receive commands from the control center and apply them to control power apparatus just as present relays are able to do. The overall design of the UMPCU is illustrated in Figure 4. The figure shows the actual flow of data and computations required.

It is emphasized that the proposed approach facilitates efficient communications. Specifically, each substation sends to the EMS only its real time model which comprises a very small number of data. When connectivity changes, then connectivity data are transmitted by exception. Similarly if model changes occur, the new mathematical model will be transmitted by exception. The end result is that while the instrumentation may be collecting data at rates of hundreds of thousands of data points per second, the frequency domain state (phasors) are only a few tens of data points per second. Only the frequency domain component state is transmitted to the EMS.

The constituent parts of this approach are described next.

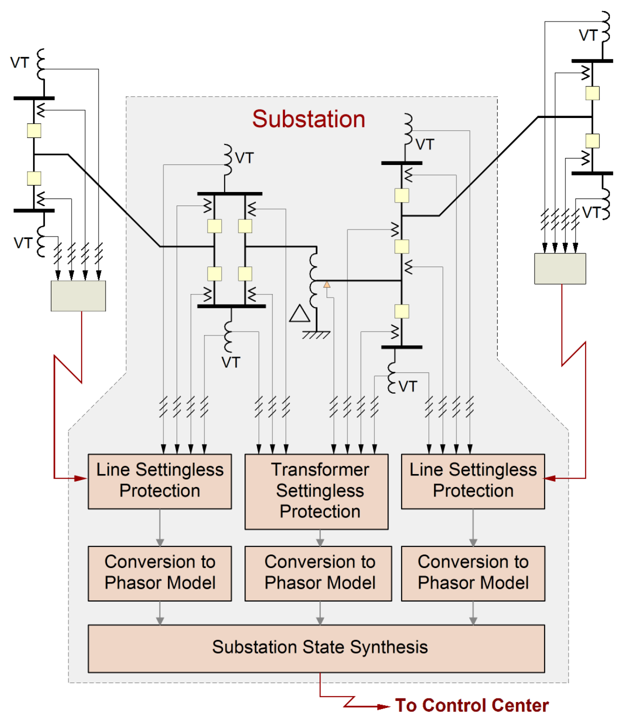


Figure 1: Illustration of Overall Approach

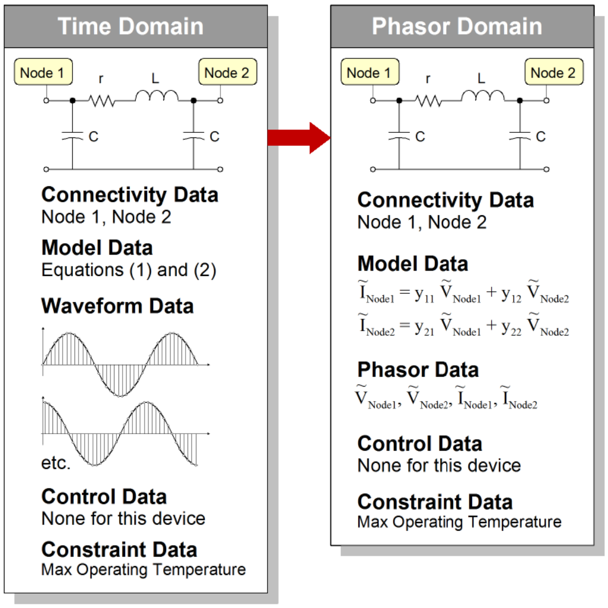


Figure 2: Simplified Example of Time Domain Model into Phasor Domain Model

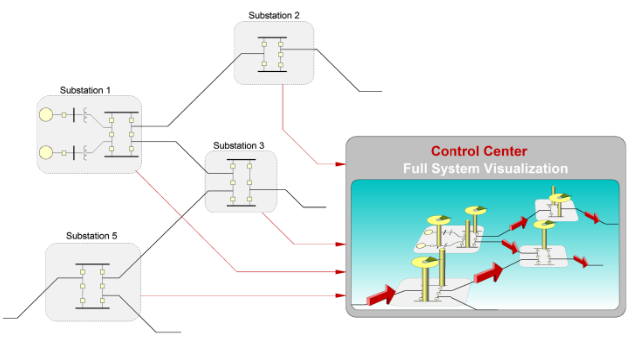


Figure 3: Synthesis of System Wide State Estimate from Substation State Estimates

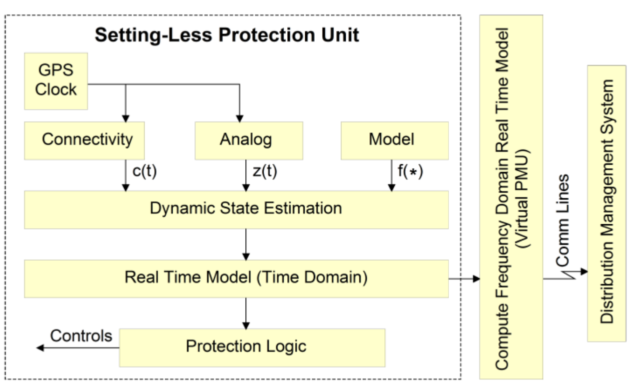


Figure 4: Functional Diagram of Setting-less Protection Unit

State and Control Algebraic Quadratized Companion Form

The model of a component in general is expressed as a set of differential and algebraic equations in terms of state and control (continuous and/or discrete) variables. For object orientation a standard form for any device must be developed. For this purpose, we have developed the following procedure. First the model equations are quadratized: this process is relatively simple, any nonlinear expressions above degree two are reduced to degree not higher than two by the introduction of additional variables. Subsequently, the resulting differential and algebraic equations are integrated (we use quadratic integration, i.e. three point collocation method) to convert these equations into a set of algebraic quadratic equations. The resultant equations are solved for the through variables of the device and take the form shown in equation (1). Any measurements of specific variables or combination of variables by meters and other intelligent electronic devices are expressed in terms of the variables in equations (1), yielding the "measurement" equations expressed in (2). We refer to the two sets of equations (1) and (2) as the State and Control Algebraic Quadratic Companion Form (SCAQCF). The procedure for the automatic computation of the integrated SCAQCF model can be found in [6-7].

$$I(\mathbf{x},\mathbf{u}) = Y_{eq,x}\mathbf{x} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F_{eq,x}^i \mathbf{x} \\ \vdots \end{Bmatrix} + Y_{eq,u}\mathbf{u} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F_{eq,u}^i \mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F_{eq,xu}^i \mathbf{u} \\ \vdots \end{Bmatrix} - B_{eq} \quad (1)$$

$$\mathbf{y}(\mathbf{x},\mathbf{u}) = Y_{m,x}\mathbf{x} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F_{m,x}^i \mathbf{x} \\ \vdots \end{Bmatrix} + Y_{m,u}\mathbf{u} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F_{m,u}^i \mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F_{m,xu}^i \mathbf{u} \\ \vdots \end{Bmatrix} + C_m \quad (2)$$

where:

$I(\mathbf{x},\mathbf{u})$: the through variables of the device model.

$\mathbf{x}$: external and internal state variables of the device model,

$\mathbf{u}$: the control variables of the device model.

$Y_{eq,x}$: matrix defining the linear part for state variables.

F_{eqx} :matrices defining the quadratic part for state variables.

Y_{equ} :matrix defining the linear part for control variables.

F_{equ} :matrices defining the quadratic part for control variables.

B_{eq} : constant vector of the device model.

The main advantage of the SCAQCF model is that this formulation gives the generalized and abstract model for any component of the power system, which is independent of the type of the device and is suitable for implementation of object-oriented algorithms for any application. This generalization enables standardization for utilizing and exchanging the model of a device for other advanced smart grid applications in the proposed

EMS which will be discussed in the following sections. Any new resource of component added to the system will be automatically accounted in the advanced application as long as its model is presented in the SCAQCF syntax.

Zone Protection and Model Validation

The SCAQCF discussed in the previous part enables an object-oriented implementation of a more reliable and secure protection scheme that continuously monitors the dynamic model of the component under protection. This is achieved with a Distributed Dynamic State Estimation (DSE) that operates on each device independently using the instrumentation for protection of the device, and the outputs of this distributed state estimator are the real time model and accurate operating condition of the device which consists of (a) autonomously defined states and control variables of the component, (b) fixed syntax SCAQCF model of the component as described in previous section, and (c) connectivity information. We require that at least one data acquisition system is GPS synchronized. In this case the real time model of the device is computed at a common time reference (UTC time).

The protection function described above is referred to as "setting-less protection" because it simplifies the settings of the protection function and it does not require coordination with protection functions of other devices. The method is described in detail in [5]. The basic idea here is that the “setting-less protection” continuously monitors the validity of the entire mathematical model of the component under normal operations, and this monitoring is done in a systematic way by the use of dynamic state estimation. Specifically, all the physical laws that a component must obey are expressed in the dynamic mathematical model of the component in the form of the SCAQCF. If the mathematical model of the un-faulted component under protection is violated, it indicates a faulty condition for this component. In this case the dynamic state estimation will capture this violation by the well-known chi-square test which calculates the probability that the measurement data are consistent with the un-faulted mathematical component model. Figure5 illustrates this concept. It is emphasized that in the dynamic state estimation, the component dynamic model is converted into the SCAQCF model and this enables an object-oriented implementation of the DSE regarding less the specific type of the device and it reduces the complexity of the DSE. The details of the approach are discussed in [8-11].

In general, the proposed method can identify any internal abnormality of the component within milliseconds; the trip decision may depend on other considerations, such as typical delays for secure breaker operation, avoidance on tripping on transients, etc. Furthermore, the proposed scheme improves protection security because a relay does not trip in the event of normal behavior of the component, for example inrush currents or over excitation currents in case of transformers, since in these cases the method produces a high confidence level that the normal behavior of the component is consistent with the model of the component. Note also that the method does not require any settings or any coordination with other relays.

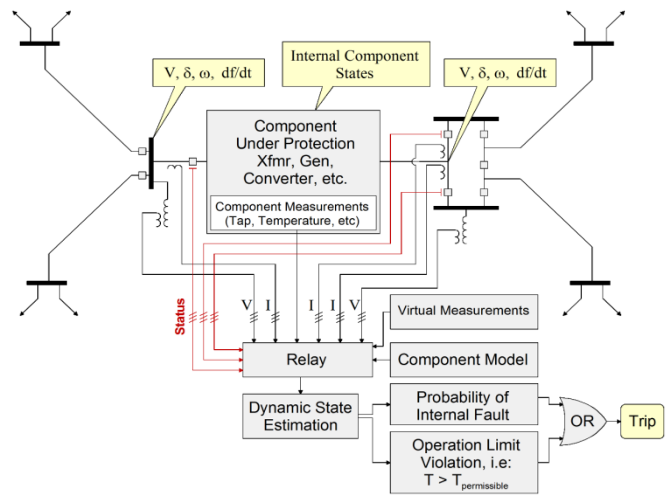


Figure 5:Illustration of Setting-less Protection Scheme via Dynamic State Estimation

Model Parameter Identification

Modeling accuracy and fidelity is fundamental in this approach. For success the model must be high fidelity so that the component state estimator will reliably determine the operating status (and therefore the health) of the component. For example consider a transformer during energization. The transformer will experience high in-rush currents that represent a tolerable operating condition and therefore no relay action should occur. The component state estimator should be able to "track" the in-rush current and determine that they represent a tolerable operating condition. This requires a transformer model that accurately models saturation and in-rush current in the transformer.

For many power system components, high fidelity models exist. For some newer components such as inverter interfaced power components, the modeling accuracy may not be as high. In both cases the state estimation process can be utilized the fine tune the models and/or determine the parameters of the model with greater accuracy. These procedures have been demonstrated in [12]. The basic approach is to expand the dynamic state estimator to include as parameters to be estimated some key model parameters. Therefore the overall approach can also provide better models with field validated parameters.

We can foresee the possibility that a high fidelity model used for protective relaying can be used as the main depository of the component model which can provide the appropriate model for other applications. For example for EMS applications, a positive sequence model can be computed from the high fidelity model and send to the EMS data base. The advantage of this approach will be that the EMS model will come from a field validated model (the utilization of the model by the relay in real time provide the validation of the model). This overall approach is shown in Figure 6.

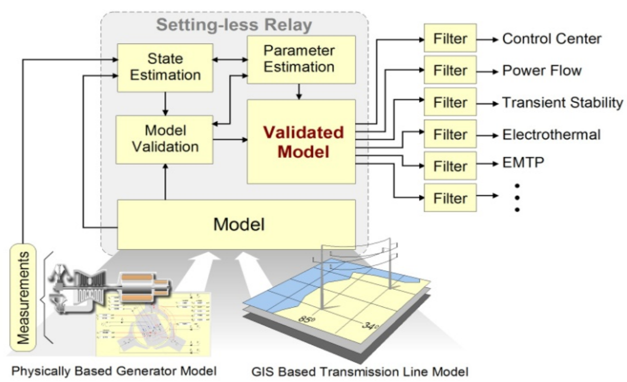


Figure 6: Illustration of Setting-less Protection Logic

Since protection is ubiquitous, it makes economic sense to use relays for distributed model data base that provides the capability of perpetual model validation.

The most important advantage is that the approach creates a depository of a high fidelity component model which in turn can provide the model for any possible application, from EMTP type studies to the simpler models required by control center applications.

Substation Model Synthesis

The results of the dynamic state estimation over a period of one cycle are in the time domain. Specifically, the point on wave data is available for each variable of the zone under protection. This data are converted into the frequency domain by applying Fourier transform on the time domain data over a user specified time interval, for example one cycle. Because the frequency of the system may vary in real time, the Fourier transform must estimate the frequency first and then perform the Fourier analysis. Otherwise issues of spectral leakage may appear. We have developed a generalized approach for the computation of the phasors that provide high accuracy in phasor computation under varying frequency and waveform distortion. We refer to this method as the "Standard PMU". The standard PMU is the subject of a paper to be released in the near future. The end result of these computations is the zone model in frequency domain. The over organization is shown in Figures 2 and 4. The phasor model is expressed in terms of five sets of data: ((1) connectivity, (2) device model, (3) measurements, (4) controls, and (5) operating limits) that are time stamped. Subsequently, this information is used to synthesize the substation state estimate. This process is quite simple: the state estimates of each protection zone are aligned by the time stamp. The zone models of a specific time stamp are collected to form the substation state estimate. In our work we use a time interval of one cycle and therefore the substation state synthesis is updated once per cycle (in reality it is updated once per (1/f) seconds where f is the nominal system frequency). Finally the substation state is transmitted to the control center where the system state is synthesized. Note that the synthesis of the substation state does not require additional computations since the component models are all in UTC time (due to the GPS synchronized measurements) and therefore they can be simply merged to provide the substation model.

System Wide Model Synthesis

The substation state estimate (in frequency domain) is used to directly synthesize the state of the entire system. This process is similar to the synthesis of the substation state estimate with the only difference that since the substation states are already in frequency domain this synthesis is straightforward and does not require any model conversions. The synthesis of the system wide state estimate is illustrated in Figure 3.Figure 3 illustrates how the EMS synthesizes the system wide model from substation state estimates. Each component's connectivity data is used to compose the topology of the substation. Using that topology, state estimates from each component that have the same GPS time stamp are immediately combined (with no additional calculations) to obtain the system wide state estimate.

Applications

The proposed infrastructure provides in an autonomous manner the real time model of components (zones), substation and system wide. This temporal and spatial real time model can be used for a variety of applications along temporal frames as well as spatial frames. Some examples are discussed here.

First the real time model can be used on demand for a number of off line applications. For example if a transient stability analysis is needed, then the real time model can be extracted in the form that is required from the particular analysis program to be used via a filter that takes the three phase real time model and creates the model in the form required. This is illustrated in Fig.6. It is important to note that any standard analysis program can be supported by simply building the filters from the real time model to the model required by the analysis program.

The importance of the proposed infrastructure is that it enables the seamless integration of real time applications. The applications use the real time model which is also characterized with the accuracy or the expected error in the real time model. Normally the expected error in the real time model is quite low providing a high confidence level on the results of the real time applications. In this paper we describe the following real time applications:(a) system protection, (b)stability monitoring, and(c) voltage/var control and optimization.

These applications have been implemented in a fully autonomous and object oriented manner. The only user interface is the selection of specific objectives, for example for the voltage/VAR control problem, the user may specify voltage profile optimization, minimum losses, or minimum operating cost. The implementation of these applications is described as follows.

Application1: Setting-less Protection

This section presents numerical experiment results of setting-less protection for power lines. A test system has been used for numerical experiments that include the line under protection and an integrated system around it. For the numerical experiments of setting-less protection the system around the line under protection is not important. The line is 115kV rated with a length of 32.6 miles. Three PTs and three CTs exist at both ends of the transmission line feeding the relays at these ends as it is shown in Fig. 6. It is assumed that the relays have PMU capability and they are streaming the measurement data to each other via fiber optic lines.

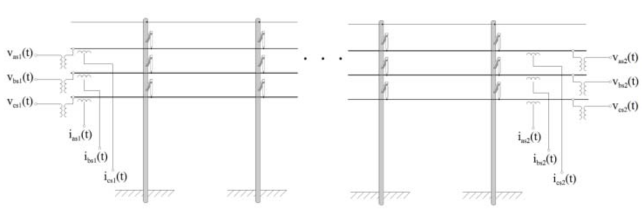


Figure 6: Test System for Numerical Experiments—Power Line

The numerical experiments are performed as follows. First a specific event is simulated and the results (the readings of the six PTs and six CTs) are stored in a COMTRADE file. The event may include faults, changes in operating conditions, dynamic load changes, high impedance faults, etc. The setting-less protection relay is initialized with the SCAQCF model of the power line. Subsequently, the proposed setting-less protection relay reads the data from the COMTRADE file. Then the state estimation algorithm is executed and the chi-square test is performed to provide the confidence level. The results for only one event are presented next due to space limitations.

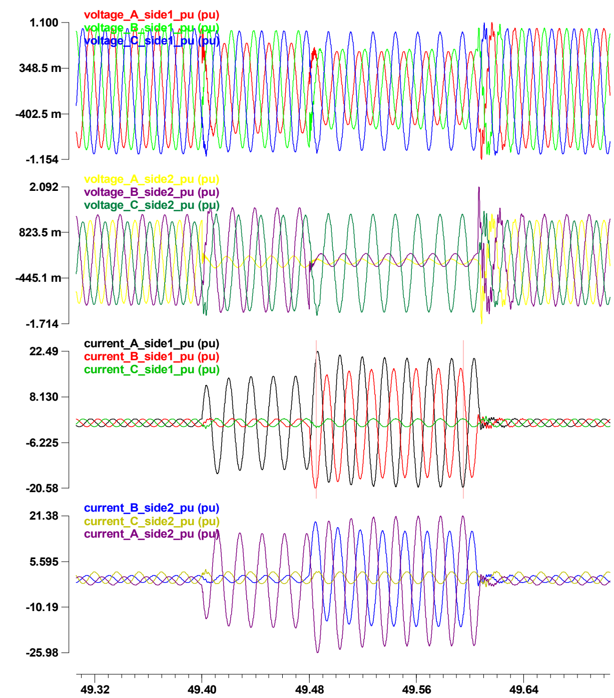


Figure 7a: Simulation Results - External Fault: 49.4 to 49.61 sec

An event was simulated that includes an outside phase to ground fault at 49.4 sec that was cleared at 49.6 sec (another external fault at 49.48 sec that was also cleared at 49.6 sec), followed by an high impedance fault starting at 52.28 sec and cleared at 52.39 sec, which is inside the transmission line under protection. Figures 7a and 7b illustrate the simulation results (zoomed in to the two faults respectively). Figure 8a depicts representative results of the setting-less protection relay for the external fault, specifically the estimated voltages at side 1 (blue), together with measured voltages at side 1 (red), and confidence level (green). As indicated in Fig.8a, the health of the monitored power line is high with 100% confidence level during the normal and through fault operating conditions. During the initiation of the external fault and fault transitions, transient voltages and currents result in 0% confidence level for a short period of time (fraction of half cycle). For the remaining period of the fault conditions, the confidence level is 100% indicating that the fault is external to the power line. The relay will not trip.

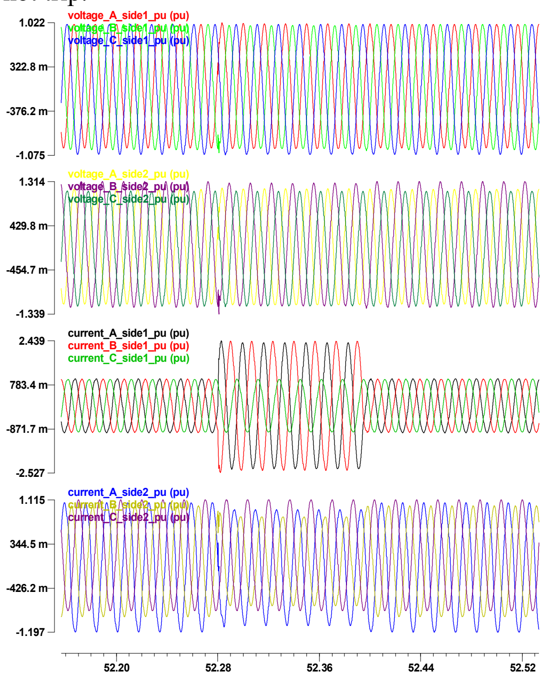


Figure 7b: Simulation Results - Internal Fault: 52.28 to 52.39 sec

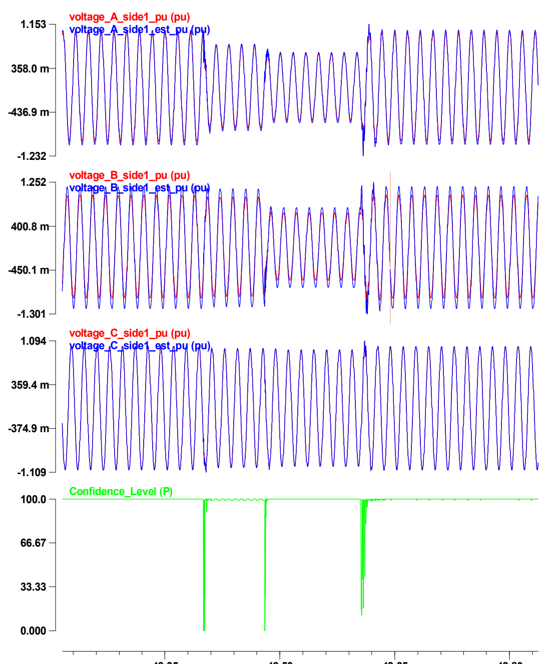


Figure 8a: Measured / Estimated Values and Confidence Level - No Trip

Figure 8b depicts the results for the internal high impedance fault. It is clearly seen that even if the currents increase only slightly, the confidence level drops to 0%, thus the relay will trip. Note that the relay is able to determine the internal fault even if the disturbance is very small. Conventional protection schemes will not detect this type of fault. As an example consider distance protection. For this line the impedance seen by the relay during this high impedance fault is 258 miles which is much higher than the length of the line and therefore a distance protective relay on this line will totally miss this fault. Similarly, today we have the technology to apply differential protection on a line. The conventional differential protection for lines uses settings of 20 to 40% restraining. Assuming perfect instrumentation, the operating current in this case is only 2% of the restraining current and therefore the fault will be completely missed by line differential protection schemes.

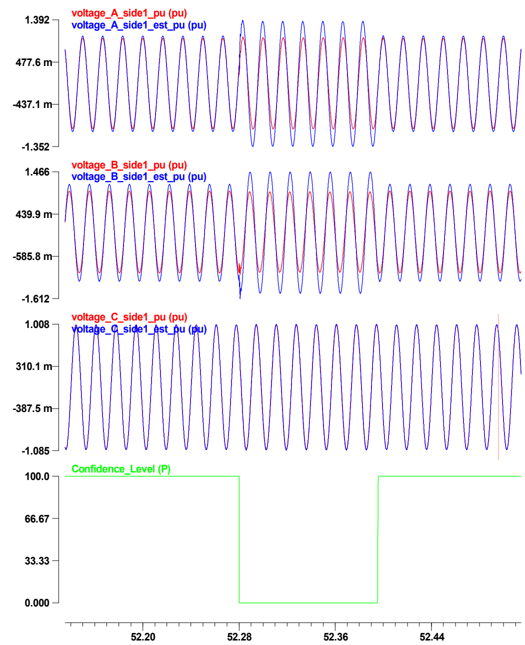


Figure 8b: Measured / Estimated Values and Confidence Level - Trip

Application2: Stability Monitoring

Previous work [12-15] has demonstrated that the results of the dynamic state estimator can be utilized to predict the transient stability or instability of a generator. Specifically the synthesized system model provides the basis for a seamless evaluation of the center of oscillations of a generating unit against the system. From this information the potential energy of a generator can be computed as a generalization of the basic energy function method. The total energy of the generator can also be trivially computed once the potential energy has been computed. The total energy is then compared to the potential energy of the generator – if the total energy is higher than the peak (barrier) value of the potential energy this indicates that the generator will lose its synchronism (transient instability). It is important to note that this approach is predictive, i.e. it identifies a transient instability before it occurs [14]. In addition, the dynamic state of the system can be utilized to predict what relays will operate (recall that the proposed approach operates on a three-phase, breaker-oriented and instrumentation and relay inclusive model and therefore can determine which relay will operate for a specific condition and what will be the system post relay/breaker operation). Knowledge of the post operation system topology, the potential energy of the generator can be computed for the post operation condition as well. This approach determines when the generator becomes unstable for the specific relay operation even in the case of successfully clearing a fault.

Various visualization techniques for the results of the transient stability monitoring have been developed. One such visualization is illustrated in Fig. 9. The center of oscillations is represented by a horizontal plane. Each generating unit is represented by a sphere. The vertical position of the sphere represents the generator phase angle δ. The generator speed is represented by an arrow. The image is animated thus representing the system status in real time.

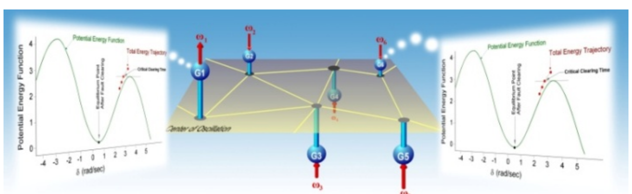


Figure9: Visualization of Transient Stability

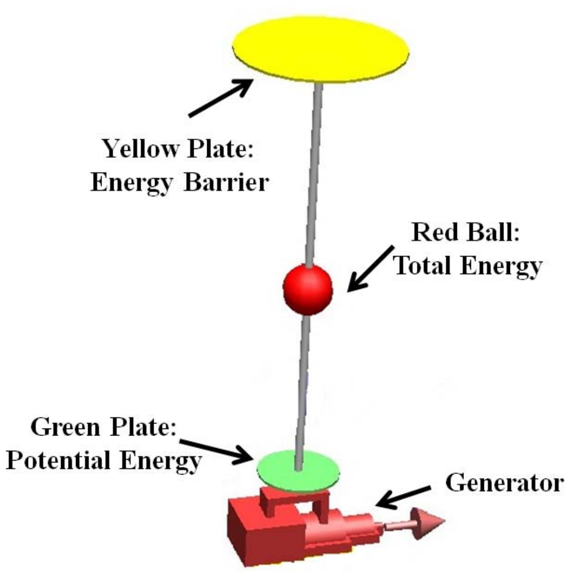


Figure10: Visualization of Individual Generator Transient Stability Status

Another visualization is for an individual generator stability status. This visualization is shown in Figure 10. It shows the energy barrier value (in terms of a yellow disk), the potential energy of the generator as a green plate and the total energy of the generator as a red ball. As the system operates and the unit oscillates, the potential energy of the generator changes, the total energy of the unit changes but the barrier is quasi-stationary unless a change occurs in the system, such as a breaker opens/closes. The visualization provides information of how close the unit is to de-synchronization. An example of this visualization will be played back at the presentation of the paper with data captured from a four unit generating plant.

Application3: Voltage/Var Optimization

The synthesized real time model of the system can be used for the voltage/VAR control problem. We consider the voltage/VAR problem as consisting of two computational procedures of interest: (a) determination of how close the system is to voltage collapse and (b) what is the optimal scheduling of the VAR resources to optimize system voltages. Both of these computational procedures can be seamlessly applied to the real time model provided by the proposed infrastructure. Some examples are presented below:

Voltage Stability Limit: The stability limit can be readily computed from the model of the system and a projected increase of electric loads. The proposed infrastructure provides the model of the system. We propose to use a reduced system model consisting of the substations that are two substations away from the substation of interest and a "State and Conrol Equivalent" model at the boundary substations. The State and Control Equivalent model is provided by the system wide model, as follows: the system wide model, except the system of interest is linerarized with respect to state and control variables. Subsequently, only a small number of state and control variables are maintained (within a certain electrical distance from the subsystem of interest) and the remaining state and control variables are eliminated. The load increase model may be a forecast or an arbitrary load increase model. Using a continuation power flow on the reduced model, the voltage versus load function is computed for the specific operating conditions. This provides the limit of load support capability and at what load the voltage will collapse. In addition the model provides the sensitivity of VAR requirements versus electric load. When this sensitivity becomes more than 50% it is concluded that the system becomes prone to voltage collapse. It is important to note that since much of the load is represented with electric motors, a realistic evaluation of the voltage magnitude variation vs. load is obtained.

Reactive Power Optimization: This problem is typically formulated as an optimal power flow (OPF) problem with the objective of levelizing the voltage profile or minimizing transmission losses. Key to this problem is a proper and reliable model of the system. Our approach is to use the proposed infrastructure to provide the real time model of a user selected area and represent the rest of the system with the "State and Control Equivalent" model computed from the system wide model, as described in the previous paragraph. An example of the State and Control Equivalent model is shown in Figure 11. In this way the problem of optimizing the VAR resources is applied to a relatively small model and can be solved quite fast. Since the model is quadratic, the solution of the proposed method is both robust and fast. It is emphasized that the correct decisions for voltage control are dependent upon the quality of the model. This application was tested by assuming that the proposed infrastructure provided the IEEE 30 bus system is in a quadratized form, as shown in Figure 11. The system was loaded heavily, to demonstrate how the approach is able to correctly handle line ratings and generator active and reactive limits. Subsequently, a 10 MVA Wind Farm was added at bus 8, to demonstrate how the object oriented real time system model synthesis is able to handle this new resource and incorporate its capabilities to the voltage/var control problem, thus reaching a better optimal operating point. For illustrative purposes, it is assumed that the power output of this wind farm is 0 MW, thus it is able to support the system with reactive power injection of up to 10 MVAr from its power electronics converter.

The maximum allowable bus voltage in this solution is 1.05 pu and the minimum is 0.95. The optimal voltage/var control solution for the system of Figure 11 with the State and Control Equivalent model representing the rest of the system is presented in Tables 1 through 6.

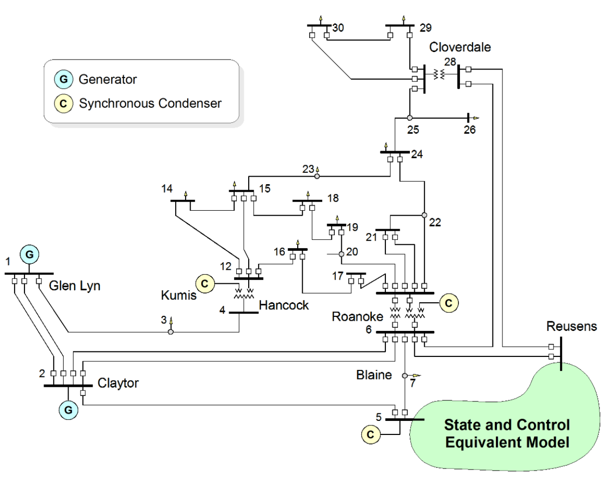


Figure 11: The IEEE 30 bus system

TABLE 1: OPF SYSTEM RESULTS SUMMARY

Overall Cost ($/hr)	603.81
Available Generation (MW)	335
Actual Generation (MW)	218.3
Load (MW)	213.2
Active Losses (MW)	5.1
Reactive Generation (MVAr)	126.6
Reactive Load (Mvar)	119.8

TABLE 2: OPF GENERATOR DISPATCH SUMMARY

Generator Bus	P (MW)	Q (MVAr)	Marginal Cost ($/MWr)
1	80	-7.35	3.151
2	41.66	-5.52	3.208
13	11.34	44.7	3.567
22	21.01	32.38	3.627
23	16.28	15.89	3.814
27	48	46.47	4.051

TABLE 3: OPF ACTIVE VOLTAGE CONSTRAINTS SUMMARY

Bus	V (pu)	V_{min}(pu)	V_{max}(pu)
7	0.95	0.95	1.05
25	1.05	0.95	1.05

TABLE 4: OPF ACTIVE P_G CONSTRAINTS SUMMARY

Generator #	Bus #	P_G (MW)	$P_{G,max}$ (MW)
1	1	80	80

TABLE 5: OPF ACTIVE Q_G CONSTRAINTS SUMMARY

Generator #	Bus #	Q_G (MVAr)	$Q_{G,max}$ (MVAr)
6	13	44.7	44.7

TABLE 6: OPF ACTIVE LINE RATING CONSTRAINTS SUMMARY

From	To	Apparent Power Flow (MVA)	Line Rating (MVA)
6	8	32	32
22	21	32	32
27	25	16	16

When the 10MVA wind farm at bus 8 is connected, the model of the system is updated, and the new object of component, in this case a converter interfaced wind farm is automatically synthesized within the system wide model. The voltage and var control problem is reevaluated, and the reactive support capabilities of the wind farm's converter yield a better optimal solution. The results with the wind farm connected are summarized in Tables 7 through 11.

TABLE 7: OPF SYSTEM RESULTS SUMMARY

Overall Cost ($/hr)	593.56
Available Generation (MW)	335
Actual Generation (MW)	217.5
Load (MW)	213.2
Active Losses (MW)	4.29
	117.2
Reactive Load (Mvar)	119.8

TABLE 8: OPF GENERATOR DISPATCH SUMMARY

Generator Bus	P (MW)	Q (MVAr)	Marginal Cost ($/MWr)
1	80	-6.95	3.603

2	54.64	21.43	3.662
8	0	10	-
13	15.37	29.8	3.769
22	22.26	27.88	3.783
23	15.15	6.79	3.757
27	30.06	28.26	3.751

TABLE 9: OPF ACTIVE VOLTAGE CONSTRAINTS SUMMARY

Bus	V (pu)	V_{min}(pu)	V_{max}(pu)
1	1.05	0.95	1.05
12	1.05	0.95	1.05
25	1.05	0.95	1.05

TABLE 10: OPF ACTIVE P_G CONSTRAINTS SUMMARY

Generator #	Bus #	P_G (MW)	$P_{G,max}$ (MW)
1	1	80	80

TABLE 11: OPF ACTIVE Q_G CONSTRAINTS SUMMARY

Generator #	Bus #	Q_G (MVAr)	$Q_{G,max}$ (MVAr)
7	8	10	10

The 10MVAr reactive support capabilities of the wind farm are fully utilized. The voltage and var control yields no activeline rating constraints, thus the synthesis of the wind farm to the system model indeed allows decongestion of the system's lines. Furthermore, the overall cost and active power losses are reduced and no low bus voltage constraints are active.

In a subsequent paper, this application will be further be refined and results will be presented comparing the solution obtained with the "State and Control Equivalent" model versus utilizing the entire system wide model. This issue will be addressed using large scale systems.

Future Work

The proposed infrastructure enables a fully autonomous monitoring, protection and operation of a wide area system. The approach is based on equipping the basic data acquisition systems with intelligence to collect not only data but also the component model as well as the connectivity, controls and operating constraints of the component. This information is enough for upstream applications to perform their tasks in an autonomous manner. GPS time synchronization is a requirement of the approach since the analytics require that the derived models and state estimates be time stamped with accuracy of microseconds. Further work is needed to perfect the infrastructure and to demonstrate a number of basic applications of this system. On-going research projects are focused on these tasks.

Conclusions

The basic concept and objectives of the smart grid is to utilize existing and future technologies for the purpose of increasing the level of automation and autonomy of the power system of the future. Towards this goal it is important to remove human intervention or needs for human input as much as possible to avoid the possibility of human error as the operation of the system becomes more complex and the number of players is increasing. We have proposed an infrastructure that practically eliminates human input in the process of extracting the real time model of the system and using the real time model for (a) protection and (b) model based control. The technology required for the implementation of the proposed scheme exists today.

References

[1] H. L. Storey, "Implementing an Integrated Centralized Model-Based Distribution Management System," *in Proc. 2011 IEEE PES General Meeting*, Detroit, MI, July 2011.

[2] A. Ipakchi, "Demand side and distributed resource management — Atransactive solution," *in Proc. 2011 IEEE PES General Meeting*, Detroit, MI, July 2011.

[3] A.P. Meliopoulos, G. J. Cokkinides, Z. Tan, S. Choi, Y. Lee and P. Myrda, "Setting-less Protection: Feasibility Study", in *Proc. 2013 46th Hawaii International Conference on System Sciences (HICSS)*, pp. 2345-2353, Maui, HI, Jan. 2013.

[4] A. P. Meliopoulos, G.J. Cokkinides, S. Choi, E.Farantatos, R. Huang and Y. Lee, "Symbolic integration and autonomous state estimation: Building blocks for an intelligent power grid", *in Proc. 16th International Conference on Intelligent System Application to Power Systems (ISAP)*, Greece, Sept. 2011.

[5] A. P.Meliopoulos, G. J. Cokkinides, and G.K.Stefopoulos, "Symbolic integration of dynamical systems by collocation methods," in *Proc.2005 IEEE-PES General Meeting*, pp. 817-822.

[6] A. P Meliopoulos, G. Cokkinides, R. Huang, E. Farantatos, S. Choi, Y. Lee, and X. Yu, "Smart Grid Technologies for Autonomous Operation and Control", *IEEE Transactions on Smart Gri*d, Vol. 2, Issue 1, 2011.

[7] S. Choi, B. Kim, G. J. Cokkinides, A. P. Meliopoulos, "Feasibility Study: Autonomous State Estimation in Distribution Systems", *IEEE Trans. on Power Systems*, Vol. 2, Issue 1, 2011.

[8] R. Huang, E. Farantatos, G. Cokkinides, A. P. Meliopoulos, B. Fardanesh and G. Stefopoulos, "Object-Oriented 3-Phase Distributed Dynamic State Estimator," *in Proc. 2011 IEEE PES General Meeting*, Detroit, MI, July 2011.

[9] A. P. S. Meliopoulos, G. J. Cokkinides, C. Hedrington, and T. L. Conrad, "The SuperCalibrator – A Fully Distributed State Estimator",*in Proc. 2010IEEE PES General Meeting,*Minneapolis, MN, July, 2010.

[10] A. P. Sakis Meliopoulos and G. J. Cokkinides, "Visualization and Animation of Instrumentation Channel Effects on DFR Data Accuracy," Proceedings of the 2002 Georgia Tech Fault and Disturbance Analysis Conference, Atlanta, Georgia, April 29-30, 2002

[11] A.P. Sakis Meliopoulos and George J. Cokkinides, "A Virtual Environment for Protective Relaying Evaluation and Testing," IEEE Transactions of Power Systems, Vol. 19, No. 1, pp. 104-111, February, 2004.

[12] E. Farantatos, R. Huang, G. Cokkinides, A. P. Meliopoulos, B. Fardanesh and G. Stefopoulos, "A Predictive Out of Step Protection Scheme based on PMU enabled Dynamic State

Estimation," *in Proc. 2011 IEEE PES General Meeting*, Detroit, MI, July 2011.

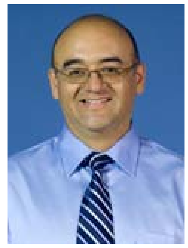
[13] A. P Meliopoulos, G. Cokkinides, R. Huang, E. Farantatos, S. Choi and Y. Lee, "Wide Area Dynamic Monitoring and Stability Controls", *in Proc. 2010Bulk Power System Dynamics and Control Symposium*, Buzios, RJ, Brazil,August 2010.

A. P. SakisMeliopoulos (M '76, SM '83, F '93) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a Georgia Power Distinguished Professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, Power Systems Grounding and Transients, Marcel Dekker, June 1988, Lightning and Overvoltage Protection, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993. He holds three patents and he has published over 220 technical papers. In 2005 he received the IEEE Richard Kaufman Award and in 2010 received the George Montefiori Award. Dr. Meliopoulos is the Chairman of the GeorgiaTech Protective Relaying Conference, a Fellow of the IEEE and a member of Sigma Xi.

George Cokkinides (M '85) was born in Athens, Greece, in 1955. He obtained the B.S., M.S., and Ph.D. degrees at the Georgia Institute of Technology in 1978, 1980, and 1985, respectively. From 1983 to 1985, he was a research engineer at the Georgia Tech Research Institute. Since 1985, he has been with the University of South Carolina where he is presently an Associate Professor of Electrical Engineering. His research interests include power system modeling and simulation, power electronics applications, power system harmonics, and measurement instrumentation. Dr. Cokkinides is a member of the IEEE/PES.

Renke Huang (S '09) was born in Wenzhou, China in 1984. He received the Bachelor Degree in Electric Power System and Automation from the Shanghai Jiao Tong University, China, in 2006 and the M.S. degree in E.C.E. from the Georgia Institute of Technology in 2009. He is currently pursuing his Ph.D. at the School of Electrical and Computer Engineering of Georgia Institute of Technology, Atlanta, GA, USA. His research interests include power systems automation, control and the application of digital signal processing technologies in power system area.

Evangelos Polymeneas (S '12) was born in Athens, Greece. He received a Diploma in ECE from National Tchnical University of Athens, Greece in 2010. He is currently pursuing his Ph.D. in the Department of Electrical and Computer Engineering, Georgia Institute of Technology. His research interests include large-scale power system estimation and control focusing on optimization of power system operation under uncertainty.



Santiago Grijalva (M'02 – SM'08) is Associate Professor of Electrical and Computer Engineering and Director of the Advanced Computational Electricity Systems (ACES) Laboratory at The Georgia Institute of Technology. His research interest is on power system control, power system informatics and economics, and intelligent energy ecosystems. From 2002 to 2009 he was with PowerWorld Corporation as a senior software architect and consultant. His obtained the Engineer degree in E.E. from EPN-Ecuador (94), M.S.I.S. from ESPE-Ecuador (97); and M.Sc.E.E. (99), Ph.D.E.E. (02) from the University of Illinois at Urbana-Champaign.

Paul Myrda is a Technical Executive with EPRI and manages the Information Communication Technology Transmission program and Grid Transformation project. Paul represents EPRI on Advisory Boards for the Power Systems Engineering and Research Council, Trustworthy Cyber Infrastructure for the Power Grid Center and North American Synchrophasor Initiative. He has an MBA from Kellogg; MSEE and BSEE from Illinois Institute of Technology, licensed professional engineer, and member of IEEE and CIGRE.

Evangelos Farantatos (St. M '06, M '13) was born in Athens, Greece in 1983. He received the Diploma in Electrical and Computer Engineering from the National Technical University of Athens, Greece, in 2006 and the M.S. in E.C.E. and Ph.D. degrees from the Georgia Institute of Technology in 2009 and 2012 respectively. He is currently a Sr. Project Engineer/Scientist at EPRI. In summer 2009, he was an intern in Midwest ISO. His research interests include power systems state estimation, protection, stability, operations, control, renewables integration and smart grid technologies.

Mel Gehrs is president of Gehrs Consulting Inc specializing in Smart Grid technology and data mining of Smart Grid data. He currently has contracts with EPRI and Silver Spring Networks. Prior to forming his own company he worked for NASA as a technology transfer specialist and then Exelon/ComEd as a nuclear and electrical engineer.