The Fundamental Concept of Unified Generalized Model and Data Representation for New Applications in the Future Grid

Mladen Kezunovic
Texas A&M University
kezunov@ece.tamu.edu

Santiago Grijalva
Georgia Institute of Technology
sgrijalva@ece.gatech.edu

Papiya Dutta
Texas A&M University
papiya82@tamu.edu

Ayusman Roy
Georgia Institute of Technology
ayusman@gatech.edu

Abstract

The concept of interoperability of data and model as presented in this paper is viewed as being very useful for implementing variety of future applications related to power system monitoring, protection, control and operation. To illustrate the proposed concept, two applications are used: state estimation and fault location. Generalized State Estimators (GSEs) consider both measurements and switching device statuses as variables to be estimated. We propose a unified generalized state estimator that uses only one class of network objects (node-breaker), which would avoid model conversions, enables unified topology processing, and supports flexible forms of generalized estimation. The proposed Fault Location (FL) application uses different types of measured data which utilizes power system static data modeled using bus-branch. Significant number of mappings is required to correlate the measured data and model. It is shown that both applications will be simplified if unified generalized representation of data and model as suggested in this paper is utilized.

1. Introduction

Interoperability is the capability of systems or units to provide and receive services and information between each other, and to use the services and information exchanged to operate effectively together in predictable ways without significant user intervention [1]. In other words, interoperability in power system context means correlating data and models expressed in different formats but having similar descriptions seamlessly, extracting useful information from them automatically, and using such information in all power system applications consistently. The outcome allows an application with the same functional description to replace the former one, and this should happen without unnecessary complicacy encountered today.

The Grid Wise Architecture Council (GWAC) proposed a context-setting interoperability framework (GWAC Stack) [2] to address interoperability requirements in eight different layers. In the scope of this paper, we are interested in layers 3-4 (Syntactic interoperability and Semantic understanding) considering unified data and information flow across different databases and applications. Understanding the data structure of the information exchanged and interpreting the information so exchanged, is required by all databases and applications if interoperability is to be achieved.

The NIST Framework and Roadmap for Smart Grid Interoperability Standards [3] presents a conceptual architectural reference model which is mostly developed for the legacy solutions not allowing full understanding of how the interoperability of data and models is going to be handled for new or enhanced applications. Developing interoperability framework of data and model for enhanced applications like new solutions for state estimation and fault location, and preparing use cases for such applications is highly needed.

To achieve interoperability a unified generalized representation of data and model is required. In the proposed approach we use standard formats to represent data and models such as: a) IEC 61850-6 SCL [4] and IEEE COMTRADE [5] for DFR data and b) CIM [6-7] for power system model & SCADA data are useful to consider achieving interoperability. As both standards use eXtensible Markup Language [8] for data representation and use node-breaker objects for power system modeling, a unified generalized representation for data and model is possible.

Several harmonization efforts to properly use all these standards can be found in literature. Formal integration of CIM and SCL by bi-directional mapping between them is addressed in [9]. Mapping specific to topology processing application is proposed in [10]. Harmonizing these two standards to develop a unified semantic model is discussed in EPRI report on the subject [11]. Use of several canonical data models (a semantic model chosen as a *unifying* model that will govern a collection of data specifications) instead of a single one is proposed in [12].

This paper addresses the need of unified generalized representation of data and model for improving existing applications of fault location and state estimation. After the background, the issues of how the data and model may be represented are discussed for each application in section 3. The conclusions and references are given at the end.

2. Background

Accurate location of transmission line fault is required to restore service after a fault as soon as possible. This paper is focused on developing interoperability of data and model for new sparse measurement based fault location [13] scheme using phasor measurements (recorded by Digital Fault Recorders) from different substations located in the vicinity where the fault has occurred as well as SCADA measurements (PI Historian archived data [14]) from all the substations near the fault. The static power system model is represented by a proprietary format (PSS/E [15]) which is based on the bus-branch model objects. Correlation of data and model requires a lot of manual mapping thereby making the interoperable implementation very hard to achieve.

Robust estimates of the power system state in real-time is essential for control and enhanced security analysis and economic optimization applications. For the state estimation application, this paper focuses on interoperability of data and model for arbitrary switching device topologies, which enables effective topology error detection. A unified model drastically simplifies identification and processing of suspect subnets, where the switching device status may be undetermined or identified as inconsistent. This is a limitation of most state estimators deployed today.

The necessity of unified generalized data and model representation in the context of the two mentioned applications will be discussed in this section.

2.1. Sparse measurement based fault location application

Typically digital fault recorders (DFRs) or digital protective relays (DPRs) are placed in substations and they record current, voltage and status signals on occurrence of an event like fault. Installing recording devices (DFRs in our case) at the ends of all the transmission lines is not economical. Although protective relays exist on every transmission line, most of them may still be electromechanical and they do not have capability to record measurements. In particular, when the lines are tapped, the measurement devices may not be placed at the tap branch. As a result, in some cases it may happen that there are no recordings at all available at line ends close to a fault. System-wide sparse measurement based fault location method can be applied in such instances [13].

In sparse measurement based fault location method, phasor measurements from different substations located in the region where the fault has occurred are used. The measurements are sparse, i.e. they may come from only some of so many transmission line ends (substations) in the region. This method requires synchronization of the measurements, which may be obtained by using DFRs connected to Global Positioning System (GPS) receivers [16].

2.1.1. Implementation. The method uses waveform matching technique between the current and voltage phasors calculated from the waveforms recorded in a substation (nearby the faulted line) and phasors obtained using short circuit simulation of possible fault locations. A commercial short circuit program toolset PSS/E^{TM} 27 is used for short circuit calculation [15]. The calculated and simulated phasors are compared while the location of the fault is changed in the short circuit program. This process is repeated automatically until the difference between measured and simulated values reaches global optimum (minimum), which indicates that the fault location used in the short circuit program is the actual one in the field. The criteria for the minimal difference are based on a global optimization technique that uses Genetic Algorithm.

The measured data and models associated with sparse measurement based fault location application are:

- **Event data:** These include event data captured by recording devices (DFRs here) after occurrence of a fault.
- **SCADA PI Historian data:** This data reflects real time changes in power system including the latest load, branch and generator data to tune the static system model with the actual pre and post fault conditions.
- **Power system static model data:** These include power flow system specification data for the establishment of a static system model (in PSS/E *.raw format).

Figure 1 describes the information flow for sparse measurement based fault location application. The measurements are collected from either substation IEDs such as digital protective relays (DPRs), digital fault recorders (DFRs) and phasor measurement units

(PMUs) or remote terminal units (RTUs). The measurements consist of status and/or analog signal of voltage and currents depending on the type of recording device. Substation IED database stores the data captured by IEDs that are triggered by the occurrence of an event. Such data is collected at a high sampling rate (millisecond range) using synchronized sampling. The RTU data is scanned continuously (not triggered by the occurrence of an event) at a relatively low scan rate (second range) are stored in SCADA database. After occurrence of a fault, fault location program locates fault in the following steps:

- Compute phasors from waveforms recorded by IEDs.
- Tune static power system model (topology and load-generation information) using SCADA data.
- Simulate phasors using short circuit program with the tuned model.
- Compute fault location by waveform matching of simulated and recorded phasors.

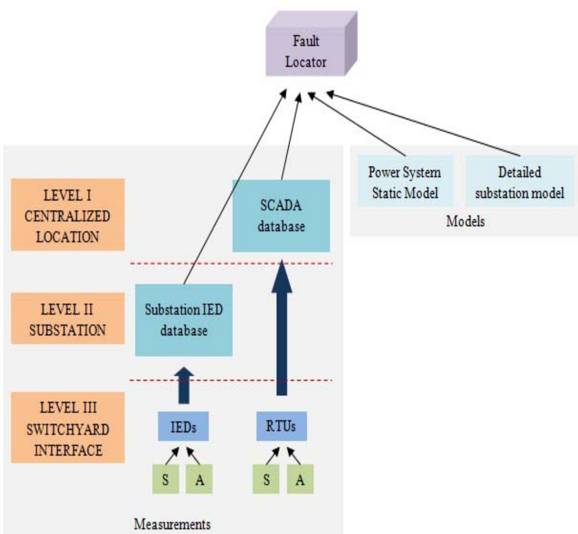

Figure 1. Information flow for fault location application

2.1.2. Need for unified generalized approach. The substations are generally modeled in detailed node-breaker objects while power system static model is based on less detailed bus-branch objects and therefore the names and numeric designations of same power system components described in those two models may become different. Again the nomenclature used in IED database follows that of substation model while nomenclature used in SCADA database follows that of static system model. It is evident that implementation of fault location application needs to communicate with all the databases and models and also between them, which sometimes results in information extraction and exchange that overlaps in terms of the model objects yet the objects are described differently. Significant number of nomenclature mapping (often done manually) is required to uniquely describe such overlapping references.

As a result, the following issues are hindering integration and interoperability of data and model for this application:

- Field data collected from various IEDs from different vendors has different data format and information contents.
- Sampling rates and techniques for IED data and SCADA PI Historian archived data sampling are different.
- The names and numeric designations are different for the same power system components.

Such differences need to be reconciled when interoperability of data and model are sought, and this has to happen at both the semantic and syntactic levels.

2.2. State estimation application

Conventional state estimators have the fundamental limitation of assuming certainty about the statuses of switching devices. In conventional EMS, Topology Processing (TP) uses the assumed statuses to convert the network model from the physical, node/breaker level to the bus/branch level model, where the state estimation computation can take place [17-18]. Plausibility checks are often used prior to the topology processing step, but those checks capture the rather obvious errors. Current distribution state estimators use the conventional topology processing architecture, too. Often, topology processing takes place off-line, making real-time topology errors catastrophic, since the correct topology cannot be realized in real-time.

2.2.1. Implementation. In previous research, a unified planning and operations application architecture has been developed for steady-state analysis. This unified architecture extends existing planning software, which inherently uses the bus/branch objects, to be used directly in real-time to solve node-breaker (operations) based models, while using a single network representation [19-20]. One of the benefits of the unified architecture is that it makes working with bus/branch or node/breaker models transparent to the application. In this manner, full unification of planning and operations business processes is achieved at three levels: power system data, power system model, and power system application. The unified architecture can be incorporated into the Generalized Sate Estimator (GSE) to achieve substantial benefits:

- Because a single node/breaker is used, no model conversion or device mapping between models needs to take place. GSE implemented using a unified architecture will handle a single node array, as opposed to various data structures needed for the objects and mappings required in a two-model framework.
- Processing of suspect regions can be done directly and at will on the node-breaker model. The method dynamically assigns pointers to process switching device subnets of arbitrary size and configuration.
- The architecture can be supported by legacy core state estimator application without requiring fundamental changes to existing numerical code.

The proposed method is compared with the conventional state estimator in Figure 2. While conventional state estimation starts after topology processing has been completed, in the unified generalized state estimator, the topology is processed or re-processed based on suspect subnets with great flexibility, enabling implementation of generalized techniques for topology error detection.

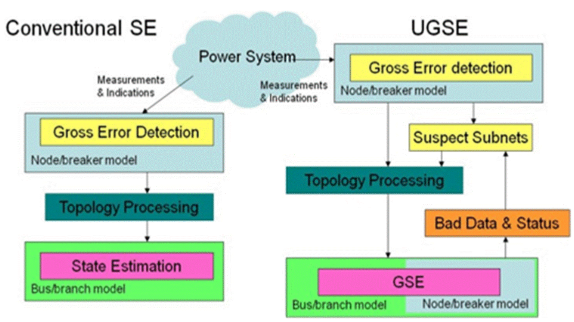

Figure 2. Proposed unified generalized state estimator concept

2.2.2. Need for unified generalized approach. The intrinsic limitation of conventional estimators was pointed out in the late nineties [21-22], which resulted in the development of the theory of Generalized State Estimators (GSE): that include breaker statuses in the set of variables to be estimated. GSEs have not been widely accepted in the industry because its implementation is cumbersome:

- Breaker status information is only available at the physical, node/breaker object level prior to topology processing. In order to identify and resolve topology errors, the GSE must handle and maintain mappings between the two node/breaker and bus/branch objects, requiring a large set of data structures and auxiliary mapping routines.
- During the solution, GSE must alter the bus/branch topology as suspect breaker statuses are processed. Thus all the mappings must be dynamically updated, which is computationally very inefficient.
- Legacy state estimators algorithms use a bus/branch model representation to perform the numerical computations, and it is not trivial to incorporate breaker information in existing code.

The intricacies of GSE can be summarized by saying that GSEs proposed so far require defining and maintaining two models. Therefore, a unified generalized description of data and model representation if implemented will reduce those individual mappings between all types of data and model which will in turn help in achieving interoperability.

3. Unified generalized representation of data and model

A unified generalized representation of data and model is discussed in this section. The proposed system architecture is shown in Figure 3.

3.1. Data representation

Three different standards are used to describe various data at the syntactic and semantic level.

IEEE COMTRADE [5]: IEEE Standard Common Format for Transient Data Exchange (COMTRADE) describes syntax of the following files extracted from the raw measurements captured by substation IEDs:

- **Configuration files (*.cfg):** information for interpreting the allocation of measured data to the equipment (input channels) for a specific substation.
- **Data files (*.dat):** analog and digital sample values for all input channels (described in configuration file) in substation.

IEC 61850-6 [4]: Substation Configuration Language (SCL) is a standard to describe substation configuration allowing semantic interpretation of substation data. The following files types are the components of SCL:

- **System Specification Description (SSD):** single line diagram of substation and logical nodes.
- **IED Capability Description (ICD):** capabilities of an IED.
- **Substation Configuration Description (SCD):** complete substation configuration.
- **Configured IED Description (CID):** an instantiated IED with all configuration parameters relevant to that IED.

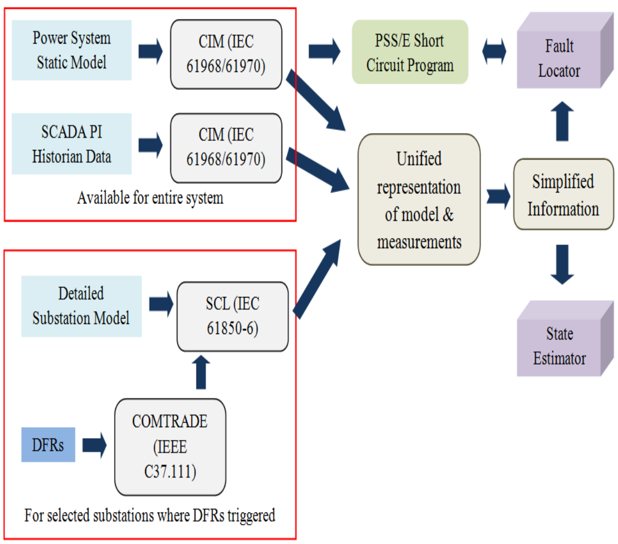

Figure 3. Proposed unified generalized representation of data and model

IEC 61968/61970 [6, 7]: Common Information Model (CIM) contains semantics for data modeling and information sharing across control center applications.

As shown in Figure 3, CIM is used to describe power system static model and SCADA measurements captured by RTUs thereby sharing a common semantic understanding. Measurements captured by DFRs expressed in COMTRADE (converted using DFR assistant software [23]) to facilitate syntactic interoperability between DFRs of different vendors are represented in SCL with the help of detailed substation model. Measurements captured by other IEDS can also be represented by SCL to share a common semantics. Therefore, all data and its relationship to network model are expressed in either CIM or SCL, which both have a comprehensive syntactic and semantic interpretation. Mapping is required only to correlate between the model and data represented in CIM and that of SCL to obtain a uniform syntactic and semantic representation. All the applications can use this unified representation of model and measurement data, which then facilitates the interoperability.

The proposed data representation consists of the following:

Substation data represented by COMTRADE and SCL: As shown in Figure 4, data captured by digital fault recorder is first analyzed using DFR Assistant software [23] which can generate an analysis report (containing the type of fault and a possible faulted line) in addition to generating the COMTRADE files. The data captured in different DFRs supplied by different vendors are represented in the same format providing syntactic interoperability. But to correlate the nomenclature designations of the DFRs with that of the detailed substation model (expressed in SCL) and whole power system static data model (expressed in CIM), we need to express those COMTRADE data in SCL format. Expressing COMTRADE files in SCL format is done in the following steps (shown in Figure 4):

- COMTRADE files are used to develop IED Capability Description (ICD) file.
- On the other hand, detailed substation model is used to prepare System Specification Description (SSD) file.
- ICD and SSD files combined can create Substation Configuration Description (SCD) file which process Configured IED Description (CID) for an instantiated IED (DFR here).

Therefore all DFR data are converted to SCL format. This approach can be extended to any type of IEDs.

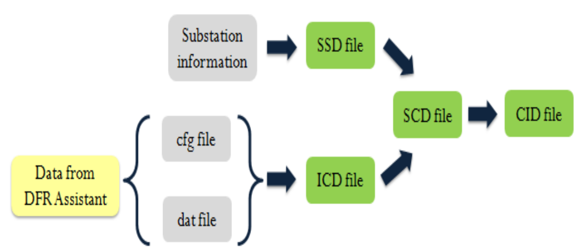

Figure 4. Substation data preparation

SCADA data represented by CIM: CIM is an abstract model that represents all objects related to EMS. It defines classes and attributes for all these objects and their relationship using unified model language (UML) representation. Related model elements within CIM are grouped in packages. The top level packages are: Core, Topology, Wires, Outages, Protection, Measurements, Load Model, Generation, Production, Generation Dynamics, SCADA and Domain. SCADA package composed of classes that contain model data points (sources of SCADA data). The measurements captured by RTUs describe the connectivity model represented in the Wires Package with the associated Measurement class from the SCADA package [24]. The part of the CIM-XML file corresponds to these objects are called CIM dynamic file while the rest are CIM static file. CIM dynamic file is much smaller in size compared to CIM static file and therefore easy to handle for real time operations.

In summary, all types of captured data are represented in either of two semantic models: CIM or SCL. Common semantic understanding is possible within each model and mapping is required to achieve that between the two.

3.2. Unified generalized representation

Power system static model is represented using a node-breaker CIM static file. The detailed substation model is represented in SCL format. A nomenclature mapping of CIM static file and SCL static file is done for correlation. As both semantic models are expressed at the same level of detail, a lossless harmonization is possible. At this level, the semantic meaning is correlated. As the fault location application still uses short circuit program which needs power system model in PSS/E format using bus-branch objects, the model is extracted from the detailed CIM static file [24] through a uni-directional translation. State estimation application also requires representation of power system static data of both bus-branch and node-breaker objects.

A unified generalized representation of data and models is discussed in detail next. The representation has two parts:

3.3.1. Nomenclature mapping. As all data and models are now converted to detailed node-breaker representation, automatic nomenclature mapping between substation data and power system static model and SCADA data is possible. This facilitates the syntactic and semantic interpretation of data. All data and models can share uniform nomenclature of power system components and devices thereby simplifying the information exchange.

3.3.2. Unified modeling. Unified modeling to correlate node-breaker and bus-branch objects is discussed in this section. Fault locator application requires short circuit program modeled in PSS/E format which follows bus-branch objects. The state estimator on the other hand is represented by CIM using node-breaker objects, but the numerical solution requires a bus-branch representation to avoid the effect of zero or low impedance branches in the measurement Jacobian. The conventional approach is therefore to utilize two classes: nodes and buses. This results in an array of nodes and another array of buses, which form the basis for the node-breaker or bus-branch model representations. This facilitates unique matching between data and models.

In order to realize model unification, a mechanism must be found to be able to see the network in the full detail provided by the node-breaker objects, but at the same time be able to numerically solve the network handling switching devices. What is proposed to obtain a unified model is to use a single node class, a single array containing nodes, and correspondingly a single (unified) model. No bus class or bus array exists at any time.

This is illustrated in Figure 5, which shows how dynamically handling device terminal pointers allows a node-breaker model to be consolidated into the electrically equivalent of a bus-branch view using exclusively nodes. In Figure 5.A buses are shown as green boxes containing groups of nodes connected through closed breakers. In Figure 5.B, the terminals of devices have been moved to a selected primary node. In Figure 5.C, the breakers and the non-primary nodes have been removed. The three networks A, B, and C are electrically equivalent, and only nodes are used as the basis to represent each network.

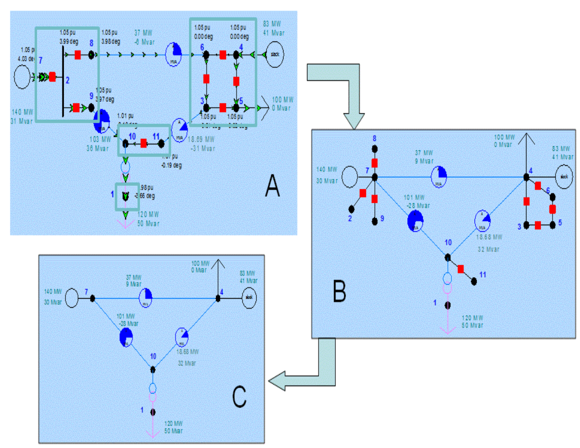

Figure 5: Realization of unified generalized representation

With the proposed approach we have obtained transparency in the model description, which leads to unified model representation for either type of the network objects. Combined with the generalized representation of data and model using SCL and CIM mapping, the main requirements for the syntactic and semantic interoperability are achieved.

4. Conclusions

A unified generalized power system data and model representation for enhanced grid applications like state estimation and fault location brings multiple benefits:

- Correlating data captured by several substation IEDs with different model objects without any user intervention facilities achieving interoperability, a key design goal for new applications.
- Reducing significant number of mappings and data exchanges (sometimes redundant) between the models and measured data simplifies software design tremendously and makes future updates easier.
- Extracting appropriate information to use in new applications can be automated opening opportunities for the use of non-operational data for operational uses significantly enhancing situational awareness.

Achieving seamless translation between bus-branch and node-breaker model representation of power system allowing matching of field data with both real-time and planning models.

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