Cyber-Physical Energy Systems Approach for Engineering Power System State Estimation in Smart Grids

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Abstract. This investigation proposes a CPES architecture and model for engineering energy management application for smart grids. In particular, the investigation considers the implementation of the power systems state estimator (PSSE). The CPES architecture has three layers: physical, monitoring and applications. The physical layer consists of the grid and the various components. Since, the grid is usually engineered with various devices from multiple vendors that have different protocols and standards; data aggregation becomes a problem. The second layer of the CPES architecture overcomes this problem by proposing a middleware that aggregates data from the physical layer. The topmost layer is the applications layer, where the energy management system applications are implemented. These applications require the model, topology and information from the grid. This requires combining the physical aspects of the grid with the cyber ones. This investigation uses the common information model to model the grid and information exchanges. Then the model is combined with measurement and optimization models of the application to realize the PSSE. The proposed approach is illustrated on a Norwegian distribution grid in Steinkjer. Our results show that the CPES approach provides an easier way to engineer future smart grid applications.

Keywords: Cyber-physical energy systems (CPES) · Power systems state estimator (PSSE) · Common information models (CIM) · Service oriented architecture (SOA) · Middleware

1 Introduction

Traditionally, core responsibility of power engineers has been to operate power grids and manage the transfer of energy. With the advent of smart grids there is an unprecedented volume of data available that needs to be harmonized with the energy

flow. Consequently, communication and energy infrastructure have to be designed together for achieving cost benefits from smart grids. The communication infrastructure includes middleware, communication networks, data-models, and software platforms. Furthermore, since smart grids are massively distributed systems scalability plays a vital role within various applications such as state estimation, stability analysis and contingency analysis. These applications rely on measurements from heterogeneous sensors that are manufactured by various vendors. Engineering such applications requires a framework for handling both the cyber and physical parts of the grid simultaneously.

Cyber Physical Energy Systems (CPES) Approach is touted as a futuristic approach for engineering smart grids. They consider the tight coupling between the physical and cyber domains in their design. CPES is a recent research topic that has attracted significant attention [1]. Palensky et al. [2] proposed to study the modern energy systems using the CPES approach with the following categories: physical models, information technology, roles and individual behavior, and aggregated as well as stochastic models. Furthermore, proposed the use of CPES approach as a tool and method for the emerging complexities of the energy grids. While, specialized and useful tools for individual domains of the energy systems exist, there is no methodology to combine the different aspects of the energy and information. Motivated by this CPES approach has been studied for modelling and enabling various aspects of the energy grids. To our best knowledge, Ilic et al. [3] first proposed a dynamic model using the CPES approach. The proposed model greatly dependent on the cyber technologies supporting the physical system. Major contributors to the CPES modelling and design are Widl et al. [4–7]. In [4], the author studied the role of the continuous time and discrete-event CPES models for control applications such as demand response, load balancing, and energy storage management. The investigation [7] presented a co-simulation platform for components, controls, and power systems based on software applications such as (GridLAB-D, OpenModelica, PSAT, 4DIAC) for smart charging of electric vehicles. The use of CPES approach for energy optimization in buildings has been studied in [8–10]. The use of model based design methodology for validating control algorithms in a residential microgrid has been studied in [11]. The role of CPES system for electric charging applications has been studied in [12]. Similarly, reducing energy consumption by combining CPES and industry 4.0 was proposed in [13]. More recently, McCalley et al. [14, 15] surveyed the design techniques and applications of CPES.

In spite of these developments, the role of CPES approach for handling grid level applications has been minimum. Furthermore, CPES approach encapsulating both the physical and cyber domain has not been investigated. Among the various problems that can be tackled using CPES approach, we focus on the power system state estimation problem that has been studied in energy grids. The PSSE determines the most likely state of the power system from a set of measurements that are captured using supervisory control and data-acquisition systems. The role of PSSE is crucial for many energy management applications such as optimal power flow, monitoring, and contingency analysis. In addition, PSSE also provide snapshots of the network to energy management system applications developed by many third party applications. The role of PSSE in enabling optimal power flow [16, 33], bad-data detections, market

operations etc. [17, 32] has been studied in literature. Currently, there are various tools, standards and models used for capturing the various aspects of PSSE. The physical models used for PSSE have been reviewed in [18]. Among the communication standards used for modelling PSSE, IEC 61850 [19] and Common Information Models (CIM) standardized by the International Electromechanical Commission have been studied for implementing the grid. The investigation in [20] viewed PSSE as one of the applications enabled by IEC 61850 without much description about the implementation. The role of IEC 61850 in implementing PSSE for a distribution grid has been proposed in [21]. Similarly, CIM models for state estimation have been proposed in [22–24]. The recent research are converging more towards the use of CIM as a standard for data communication in smart grids (see, [25–30] and references therein).

The main contribution of the paper is a CPES architecture and model that can be used to engineer smart grids. The proposed architecture has three layers: physical, middleware and applications. The physical layer is the grid with the various sensors and devices. Typically the grid is composed of various components and devices that have various communication protocols, standards and manufactured by different vendors. Aggregating information from them is difficult. To overcome this, a middleware is used. The top layer of the CPES architecture is the application layer that needs to obtain the data from the middleware map it into the grid model. To model the grid, we use the common information model as it is easily extendable to model various aspects of the grid. The CIM model is tailored to the needs of the PSSE and is used for information exchange to the applications layer as well as among the applications. The application layer in addition contains the optimization and measurement models for mapping the physical variables of the grid. Furthermore, the implementation aspects of the PSSE in the application layer is also presented. The CIM based model maps the cyber aspects with the network topology and to the physical entities directly. Furthermore, the PSSE is also simultaneously realized in the application layer. This leads to a new approach for modelling and realizing future energy management applications. It is worth to mention here that the middleware part of the architecture is beyond the scope of this investigation and has not been treated in detail.

The paper is organized as follows. Section 2 presents the implementation aspects of the PSSE. Section 3 presents the CPES architecture and model. Section 4 presents the case study and implementation in the distribution network in Steinkjer. Conclusions and future course of investigation are discussed in Sect. 5.

2 Power System State Estimation

The main objective of a power system state estimator is to estimate the state of each bus, namely voltage magnitude and phase angle, using the set of redundant measurements, usually affected by errors. The set of phasors representing the complex bus voltages are called static state of the system. The State estimator, initially developed as an engineering tool, is slowly transforming into a decision support system that assists control and monitoring tasks. As with any estimator, the SE outcome is an approximation of the current network state. Moreover, from a high level supervisory control and data acquisition module, sensors measurements arrive with different time-granularities so

that measurements and state estimate can differ in phase. The physical component of the PSSE can be broken down into two parts: hardware and software. The hardware part consists of the SCADA system that collects the real-time information from the remote terminal units installed in various substations. RTU measurements include active and reactive power flows, power injections, current magnitude, voltage magnitude and phase angles. Figure 1 shows the hardware components of PSSE. Till recently, a direct measurement of voltage phase angles was considered impossible. Then, the introduction of phase measurement units (PMUs) has been made that measurement possible. In recent times, the PMUs have significantly improved the measurements accuracy by using the GPS to synchronize the time signals with an accuracy close to 1 μs.
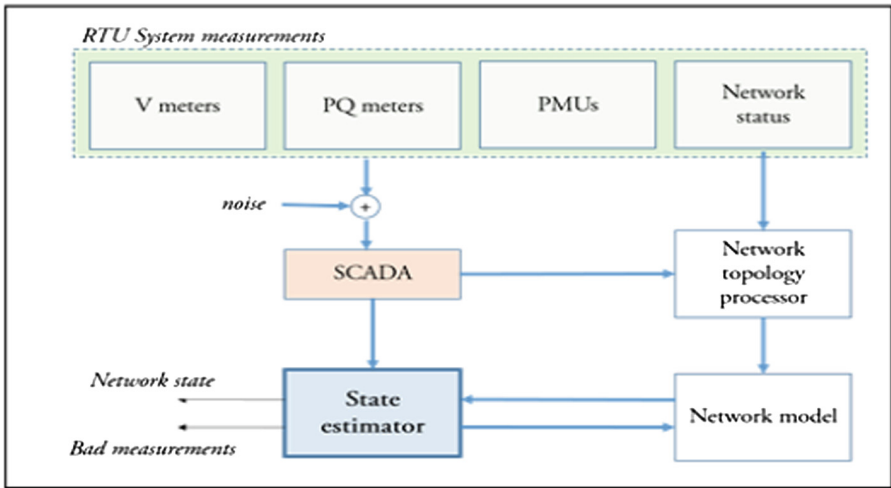

Fig. 1. Hardware components of the PSSE

The software components of the PSSE are: measurement pre-filtering, topology processor, observability analysis, state estimator, bad-data detection and bad-data suppression. The pre-filtering block checks for error measurements and unusual data. The topology processor builds the network topology required for the PSSE application using the knowledge of the physical topology. The SE algorithm then computes the state estimates. Finally, the bad data processor checks for the bad data and eliminates the error values. The state estimator block uses iterative algorithms that have finite convergence time for building the PSSE. In summary, the SE operation serves as a large-scale filter between remote measurements and high-level applications that constitute the Energy Management System (EMS).

3   CPES Model

Energy management in smart grids require orchestrating several hardware platforms, protocols and devices from multiple vendors. The EMS applications should get access to different data from these various devices. A good solution to solve the heterogeneity

issue is to design a middleware. The architecture of such a middleware is shown in Fig. 2. The bottom most layer is the physical layer that models the energy grid. The middleware aggregates the data from the grid and provides it to the PSSE application. The application layer houses the third party and other applications for EMS such as the PSSE. Energy grids typically consider the energy flows in the physical grids, however to orchestrate the smart grid, the information from heterogeneous sensors needs to be aggregated by the middleware and provided to the applications. The physical layer models the energy flows and transfers. This model needs to be augmented with the data model for implementing the EMS. The network topology and other physical aspects needs to be captured in the application layer. The flow of information among the different layers is defined by the CIM model. Here, we do not consider the implementation aspects of the middleware and the services are not elaborated. To propose the CPES model, we propose a top-down approach wherein the application layer has the PSSE application. The PSSE application requires measurements from the grid that is aggregated using the middleware. To process the information, the topology and model of the grid needs to be known. For this purpose the CIM models are used.
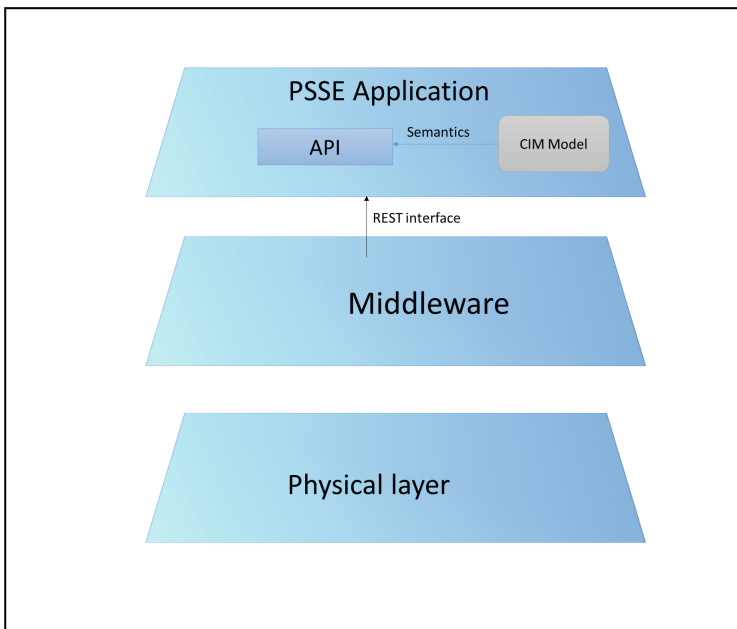

Fig. 2. CPES layered architecture

The PSSE EMS application is developed in JAVA. In order to facilitate information interoperability an application program interface (API) is defined. This API can enable different applications and services to access data and exchange information independently, alleviating difficulties with intrinsic data representation. The CIM specifies the semantics of the API. This also eliminates the difficulty of interfacing lower level

components with the physical application. The CIM model can be used to build semantics into the middleware as well. The lower level components transmit the information using dedicated communication infrastructure. There are different information models and data formats for the data. As the CIM provides interface to the applications, they are oblivious to the physical entities connected to the grid. This leads to a service oriented architecture for the middleware. In what follows we describe the measurement, optimization and grid model captured using CIM. The implementation aspects of the application layer and different aspects considered in the design of PSSE.

A. Measurement Model

The State Estimator routine is used to monitor the power network status during normal operation, where the system is in quasi-steady state responding to slowly varying load demand and power generation. It is also assumed that, in the three-phase transmission system, all loads are balanced and all transmission lines are fully transposed so that the network can be represented by its single phase equivalent diagram. Given the single phase diagram, the network is mathematically modelled and all the measurements, previously described Sect. 2, are written as function of the network state variables (i.e. voltage phasors). The equations modelling the power network are nonlinear and do not take into account all possible errors due to the uncertainties in the network parameters, e.g., metering errors and noise that may be introduced through the telecommunication systems.

Consider a vector z as the set of all available measurements. This vector can be expressed in terms of power network state variables x as follows:

$$z = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_m \end{bmatrix} = \begin{bmatrix} h_1(x_1, x_2, \ldots, x_n) \\ h_2(x_1, x_2, \ldots, x_n) \\ \vdots \\ h_n(x_1, x_2, \ldots, x_n) \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_m \end{bmatrix} = h(x) + e \qquad (1)$$

where h(x) is the measurement model, x is the state vector, and e is the error in measurements. The measurement model h(x) is a nonlinear model that maps the state vector to the measurement.

B. Optimization Model

The mathematical formulation of the presented state estimation problem is based on the maximum likelihood concept. Maximum likelihood estimator (MLE) of a random variable maximizes the likelihood function, which is defined based on assumptions of the problem formulation. The first assumption, as previously mentioned, is that the errors are distributed according to a Gaussian (or normal) distribution, with the expected value equal to zero. Thus, a random variable z is said to have a normal distribution if its probability density function $f(z)$ is given as follows:

$$f(z) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(z-\mu)/\sigma^2} \qquad (2)$$

where μ is the expected value (or mean) of $z = E(z)$ and σ is the standard deviation of z. The previous property holds for the i.i.d. assumption.

The second assumption implies that the joint probability density function (pdf) of a set of m measurements can be obtained by taking the product of individual pdfs corresponding to each measurement. The result product function is called *likelihood function* for the set of m measurements:

$$f_m(z) = f(z_1)f(z_2)\ldots f(z_m) \tag{3}$$

Essentially the likelihood function is a measure of the probability of observing a given set of measurements in vector z. For this reason we are interested in finding the parameter vector that maximize this function. In order to simplify the procedure of determining the optimum parameters, the function is commonly replaced by its logarithm, obtaining the so called *log-likelihood function*. Hence, the MLE of the state x can be found by maximizing the log-likelihood function for a given set of observations, $z_1, z_2, \ldots, z_m$. Thus, the following optimization problem is formulated:

$$\text{minimize } J(x) = \sum_{i=1}^{m} \left(\frac{z_i - \mu_i}{\sigma_i} \right)^2 \tag{4}$$

Let us define, $r_i = z_i - \mu_i$ is the residual of measurement i. The expected value $E(z_i)$ of measurement z_i, can be expressed as $\mu_i = E(z_i) = h_i(x)$, where $h_i(x)$ is a nonlinear function relating the system state vector x to the i th measurement. The minimization problem in (4) can be modelled as an optimization problem for the state vector x:

$$\min_{x} \quad \sum_{i=1}^{m} W_{ii} r_i^2 \tag{5}$$
$$\text{s.t.} \quad z_i = h_i(x) + r_i \quad \forall i = 1, \ldots, m$$

where $W_{ii} = \sigma_i^{-2}$ is the inverse of the assumed error variance for the measurements. The reciprocal of the measurement variances can be thought of weights assigned to individual measurements. High values are assigned for accurate measurements with small variance and low weight for measurements with large uncertainties. A little manipulation leads to

$$\min_{x} \quad J(x) = r^T \mathbf{W} r \tag{6}$$
$$\text{s.t.} \quad z = h(x) + r$$

where $x, r, z, h(x)$ are vectors of respective quantities and W is the diagonal weighted matrix of the WLS problem equals to the inverse of covariance matrix of the measurements.

C. Smart Grid Model

As stated earlier CIM has been chosen as a representative mechanism for the smart grid model. The CIM models provide an abstract model for the power network using unified modelling language (UML). The CIM represents the power system entities using an object oriented approach as classes, attributes, methods and association as defined in IEC 61970 [25] and IEC 61968 [26] standards. The standard IEC 61970-301 provides as semantic model for the power system components at an electrical level and their interrelationships. The IEC 61968-11 extends the semantic models to include the data exchanges for scheduling, asset management and other market operations. Although, CIM contains most classes and their associations to represent the power system, still object models need to be adapted for implementing specific application. CIM models can be adapted by defining new classes, subclasses, methods and attributes.

CIM Profile: A profile is a delimitation of CIM which consists of a subset of classes and attributes that specify information conceptually and the relationships among the different objects. A subset of IEC 61970-456 defines the CIM necessary to describe the PSSE results. A modular approach is used in the development of CIM profile that four profiles: Equipment, Measurement, Topology, and State variable Profile. The equipment profile models physical elements of the network such as network, loads, generators, and switches. The measurement profile contains the measurement information such as active and reactive power, voltages, load angles etc. Topology profile defines the classes needed to describe the network topology considering the switching status. State variable profile contains the model for defining the state variables in the network. The relationship between the different profiles is shown in Fig. 3. The profile connected at the "from" end of the arrow depends on the profile at "to" end of the arrow.
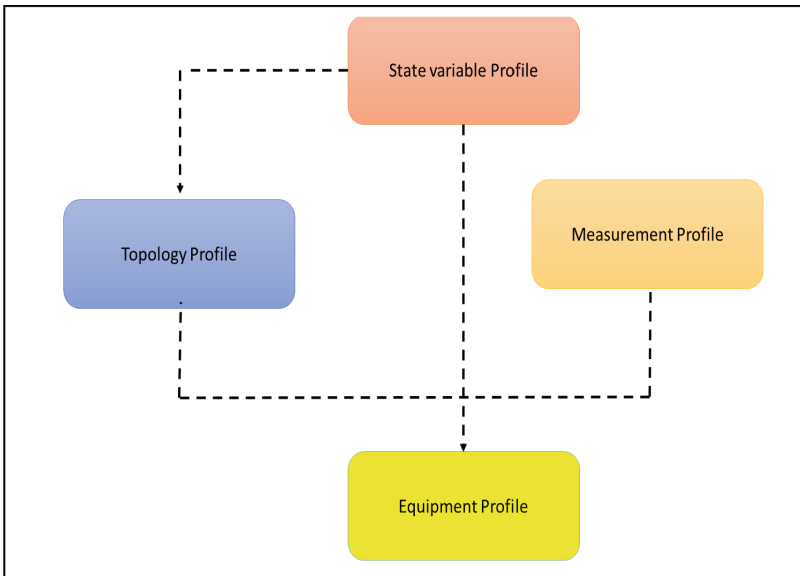

Fig. 3. CIM profiles for implementing the PSSE

As a next step the abstract and concrete classes of the various profiles are defined. As the treatment of all the profiles is beyond the scope of this investigation. Here we provide an example of the topology profile (see, Fig. 4). The topology profile defines the classes needed to describe how each of the equipment in the network is connected to each other. Topology is given by the association of the buses with the corresponding association of the terminals of the equipment. This way the network model is built as a branch flow model and can be directly used by the PSSE application. The state variable
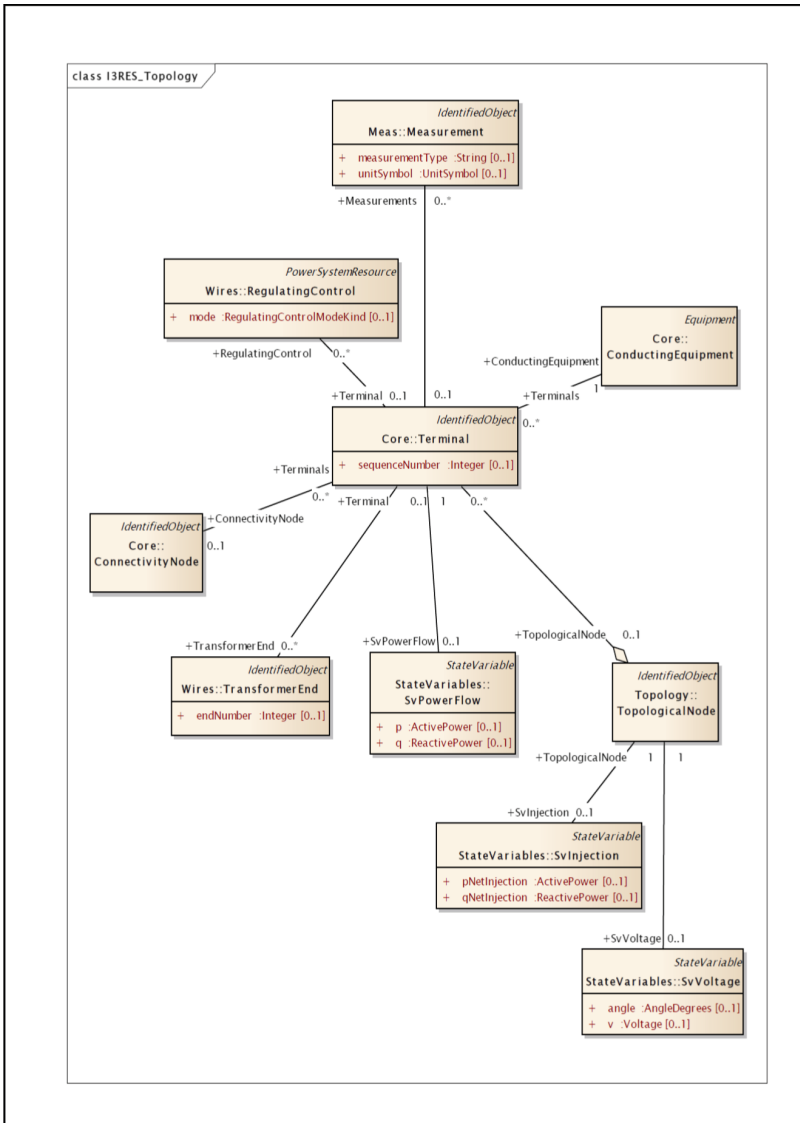

Fig. 4. Topology profile

profile of the CIM model is shown in Fig. 5. Similarly, the other CIM profiles are modelled to describe the network. In addition the abstract and concrete models required of the CIM profiles are described. The CIM model maps the network topology with the measurements and state variables. The CIM model defines the semantics for the PSSE API which is implemented in JAVA. The application uses the middleware services to query the sensors and update the network state using the PSSE application. The middleware services required can be broken down into low-level services and common services. The description of the middleware services are not considered in this investigation. REST interfaces are used to communicate between the middleware and application layer.
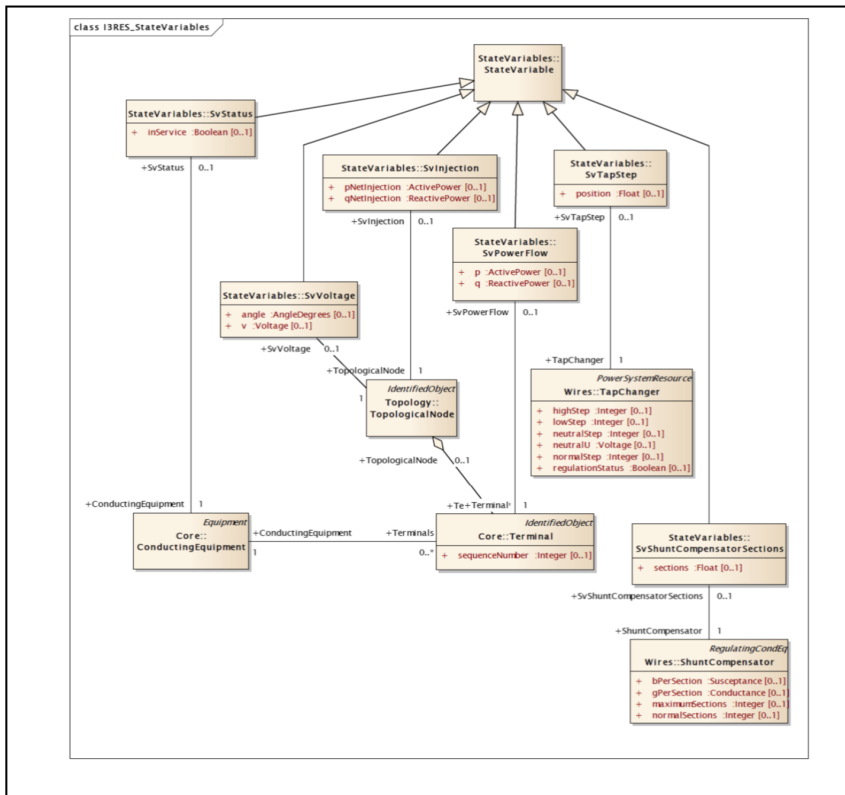

Fig. 5. State variable profile

D. Software Model of the PSSE Application

The PSSE application needs to map the data aggregated from the middleware to the network topology. To this extent the application uses the InterPSS that defines the network data in the IEEE format for processing. The application implementing the PSSE is written in JAVA and to solve the optimization model in (6) GAMS solver is

used due to its symbolic processing capability. The APIs implementing the CIM, and libraries of the InterPSS, GAMS are integrated with the application written in JAVA to realize the PSSE for the EMS.

The CPES model described above integrates the physical equations describing the energy flows in the network with the CIM to model the cyber part of the network. The resulting model encapsulates both the cyber and physical aspects of the network. Furthermore, the application software model proposed also uses the InterPSS to map the topology and uses the GAMS for realizing the PSSE. This model along with the CPES description of the network can be used to engineer energy management system application in typical smart grid. The main advantage of the proposed approach is that the method provides a comprehensive framework for co-designing both the physical and cyber aspects of the network, thereby reduces the engineering efforts. Furthermore, provides an interface between the different domain engineers involved in smart grids.

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4   Case Study

The CPES approach proposed in Sect. 3 was used to engineer PSSE in the energy management system of the distribution grid in Steinkjer, Norway. It is a radial distribution network that consists of a: hydro power plant with 2 generators, 32 aggregating loads, 50 link busses, and 84 transmission lines. The CIM defines the basic ontology of the set of attribute value pairs. Ontologies are often written in XML or in a Resource Document Framework (RDF), which is a suitable format for middleware information exchange through the common communication bus. The CIM standard IEC 61970-52 defines the procedure for description of the network model as a serialized RDF schema. The main concept of the RDF is called the tiple and consists of subject-predicate-object expression. An RDF document contains element that are identified by unique ID attribute and that can be referenced from other elements using that ID in a resource attribute. The CIM profile for implementing the PSSE can be represented using a RDF schema document. In details, after having selected all the classes, attributes and relationship among the classes, tools such as CIMTool can be used for generating the RDF schema. As stated earlier the PSSE application uses the InterPSS and GAMS to provide the state estimates for the different applications. The CIM model also defines the information exchange among the EMS applications. The CPES engineered PSSE application is tested in the pilot distribution network. The residuals of the PSSE are used to evaluate the accuracy of the state estimates. Figure 7 shows the residuals

computed for the real and reactive power in p.u. values. Our results show that the PSSE provided an accurate estimates with error between 2–4% for the 85 buses in the distribution network (Fig. 6).
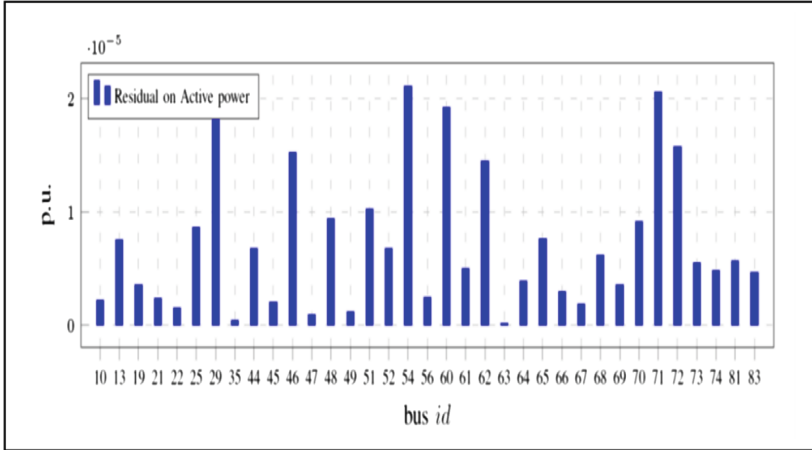

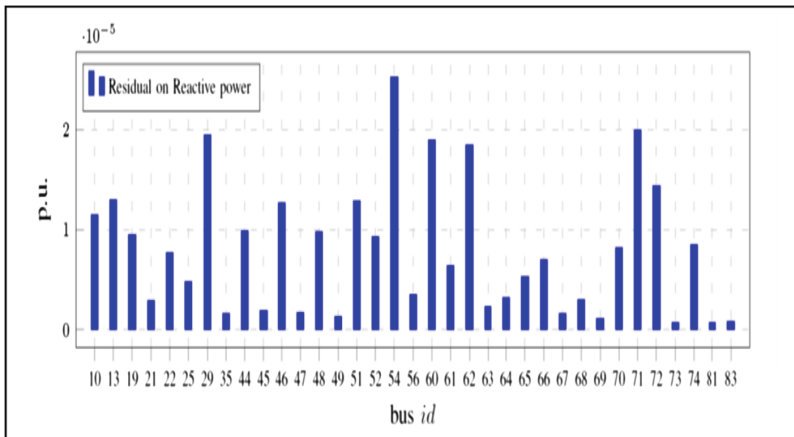**Fig. 6.** Residuals of the real power in PSSE

Fig. 7. Residuals of the reactive power in PSSE

5   Conclusions

This investigation proposed a cyber-physical energy systems approach for engineering PSSE in smart grids. The proposed approach modelled both the physical and cyber aspects of the PSSE simultaneously. The physical model was represented by the

measurement and optimization model. While, the common information model was used to describe the cyber part of the CPES model. The proposed approach can be used to engineer PSSE applications in smart grids with heterogeneous sensors from various vendors and considering interoperability constraints. Furthermore, the proposed CPES approach can also be used for building a service oriented architecture (SOA) based middleware. The details of the implementation of the middleware are not discussed in the investigation. Extending the CPES approach to model optimal power flow with PSSE is the future course of this investigation.

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