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A Cyber-Physical Systems Approach for Implementing the Receding Horizon Optimal Power Flow in Smart Grids

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Abstract—Two Major challenges in securing reliable Optimal Power Flow (OPF) operations are: *(i)* fluctuations induced due to renewable generators and energy demand, and *(ii)* interaction and interoperability among the different entities. Addressing these issues requires handling both physical (e.g., power flows) and cyber aspects (computing and communication) of the energy grids, i.e, a cyber-physical systems (CPS) approach is necessitated. First, this investigation proposes a receding horizon control (RHC) based approach for solving OPF to deal with the uncertainties. It uses forecasts on renewable generation and demand and an optimization model solving a predictive control problem to secure energy balance while meeting the network constraints. Second, to handle the interoperability issues, a middleware using common information model (CIM) for exchanging information among applications and the associated profiles are presented. CIM profiles modelling various components and aspects of the RHC based OPF is proposed. In addition, a middleware architecture and services to collect information is discussed. The proposed CPS approach is illustrated in a distribution grid in Steinkjer, Norway having 85 nodes, 700 customers, 3 hydrogenerators, and various industrial loads. Our results demonstrate the benefits of CPS approach to implement OPF addressing also the interoperability issues.

Index Terms—Cyber-Physical Systems (CPS), Common Information Model (CIM), Optimal Power Flow (OPF), Renewable Energy Systems (RES), Smart grid interoperability.

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NOMENCLATURE

Variables:

P_i^g, Q_i^g	Active and reactive power generated at bus i [p.u., p.u.];
s_{ij}	Complex power injected by node i on (i,j) [p.u.];
P_{ij},Q_{ij}	Active and reactive power injected by node i on (i,j) [p.u., p.u.];
$P^{\text{loss}}_{(i,j)}$	Active and reactive power loss on (i,j) [p.u., p.u.];
V_i, θ_i	Voltage magnitude and angle at bus i [p.u., °];
b_i	State of Charge (SOC) of the storage unit at bus i [p.u.h];
r_i	Power exchanged with the storage unit at bus i [p.u.] (positive when discharging);
$\mathcal{E}$	Set of all network transmission lines;
$\mathcal{N}_i$	Set of all buses connected to the bus i through a transmission line;

Parameters:

$y_s = g_s - \mathrm{j}b_s$	Complex series admittance for a transmission line [p.u.];
P_i^d, Q_i^d	Active and reactive power load i [p.u., p.u.];
P_i^r, Q_i^r	Renewable active and reactive power at bus i [p.u., p.u.];
$\underline{P}_i^g, \overline{P}_i^g$	Generator active power bounds at bus i [p.u.];
$\underline{Q}_i^g, \overline{Q}_i^g$	Generator reactive power bounds at bus i [p.u.];
$\overline{S}_{ij}$	Rating of line (i,j) [p.u.];
$\underline{V}_i, \overline{V}_i$	Minimum and maximum voltage magnitudes at bus i [p.u.];
$\underline{\theta}_i, \overline{\theta}_i$	Minimum and maximum phases, bus i [°];
$\underline{B}_i, \overline{B}_i$	Minimum and maximum storage unit i capacity [p.u.h];
r_i^{loss}	Storage energy loss at bus i [p.u.];
r_i^{rated}	Maximum power supplied by the storage i [p.u.];
C_i	Linear cost term of generator i [€h/p.u.];
C_i^g	Generation cost at bus i [€];
C_i^b	Storage cost at bus i [€h^{-1}/p.u.];
C_0	Models the linear and time-varying cost of the market clearing prices [€h^{-1}/p.u.];
H, T	Control horizon and simulation time [h];
ΔT	Time step [h].

1 INTRODUCTION

SMART grids (SGs) have myriads of heterogeneous components and their interoperability holds the key to their successful deployment. SGs frequently require to

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sense physical quantity and control the operations of energy components. Energy device links a cyber component (e.g., information) with the physical component (e.g., line-flows), forming a cyber-physical system (CPS) [1]. The CPS view of energy grids approach is relatively new [2] and has been used for building energy optimization [3], economic dispatch with gridable vehicles [4], control of transmission grids [5], and grid security [6] to name a few. While approaches modelling either the physical or cyber aspects of the energy grid have been studied in literature, a model that combines both these aspects needs to be explored. For example, the component models capturing both energy and data flows should be modelled. This aspect has not been fully explored in literature.

The Optimal Power Flow (OPF) is a key tool for securing energy balance in smart grids. Two challenges in implementing OPF in modern grid are: *(i)* energy management applications for implementing OPF considering fluctuations introduced by renewable generators and demand in a reliable and secure manner, and *(ii)* a communication architecture providing interoperability among devices and applications. Implementing OPF with fluctuating renewable energy sources (RES) and energy storage systems (ESS) is a challenging task. Classical OPF implementations solve a static optimization problem [7] and are not suitable for smart grids integrated with RES and ESS due to their dynamic behaviours. Researchers have studied multi-period OPF [8], an approach wherein the OPF problem is solved for multiple steps considering dynamic time-coupled behaviours of energy devices. However, the method cannot account for disturbances and forecast errors due to absence of feedback mechanism. A viable solution that overcomes this is the receding horizon control (RHC), in which the forecasts are embedded into the predictive optimization problem [9]. Such RHC implementation should be complimented by a communication architecture that promotes interoperability among application developed by different vendors on software and data bases, and a middleware to aggregate data from the physical devices, thereby making the application oblivious to the physical device. It should be noted here that, in the absence of common data formats and models, the utilities are exchanging the same data in multiple formats using dedicated communication channels for transmitting each of these data. Consequently, interoperable semantic data model becomes pivotal for exchanging information frequently among devices and applications.

The common information model (CIM) standardized by the International Electrotechnical Commission provides an abstract model for a power network using unified modelling language [10]. The CIM represents power system entities using an object oriented approach as classes, attributes, methods and association as defined in IEC 61970 [11] and IEC 61968 [12] standards. The IEC 61970-301 provides a semantic model for the power system components at an electrical level and their inter-relationships. The IEC 61968-11 extends the semantic model to include data exchanges for scheduling, asset management and other market operations. The two standards IEC 61970-301 and IEC 61968-11 together are termed as CIM and provides a foundation for building a generic model to represent all aspects of a power system, independently of any proprietary data standard or format.

Although CIM model contains most classes and their associations to represent power system, still the object models have to be tailored/extended for implementing specific applications. Extensions of CIM to Green Button Standard [13], electrical distribution system [14], state estimation [15], and business process models for Indian utility [16] have been studied in literature. To our best knowledge CIM extensions for achieving interoperability among applications has not been studied in literature. In particular, CIM profiles for defining energy storage systems, renewable energy sources, wind/hydro turbines for use in RHC based ACOPF have not been studied in existing works.

While data models are important for exchanging information among the different applications, the communication infrastructure should also have capability to aggregate data from heterogeneous lower level devices [17]: a middleware is typically used for this purpose. Many middleware proposals have been studied in literature such as the GridStat [18], SmarC [19], and CoSGrid (Controlling the Smart Grid) [20] to name a few. In these proposals only the software aspects of the middleware are discussed. Use of the middleware with data models such as CIM or an energy management application has not been studied.

A review of literature reveals that- though significant efforts have been dedicated to formulating, standardizing, and deploying OPF applications in the smart grids - still there is a disconnect between the cyber and physical world, that needs to be addressed. When RHC based OPF is used as management tool in energy grids using real-time measurements, it is essential to consider both the physical and the cyber aspects. This is important as the RHC implementation requires: exchanging network topology information with the grid, aggregate real-time measurements from heterogeneous devices, information exchange with other energy management systems (EMS) applications (e.g., forecasting tool), and semantic capabilities to organize data for particular applications. The CIM provides a standardized way to exchange data among EMS applications and a meta-model for the data that can be used for deploying ACOPF. The main idea of this investigation is to combine the physical aspects capturing the energy flows modelled using dynamical equations and the cyber aspects using CIM. Both these models are integrated into one framework in the EMS using a middleware services. Further, the CIM by providing semantics through use of ontology helps organizing data for EMS applications. The main contributions of this investigation are: *(i)* A RHC based OPF formulation that embeds forecast information on renewable generation and demand, and uses a simple power system state estimator (PSSE) for providing the necessary measurements, *(ii)* the description of a communication infrastructure comprising a middleware for aggregating data from sensors, and a CIM component library, called *I3RES Profile*, that defines data models for information exchange among different applications, *(iii)* the actual use of our CPS approach to model both energy and information flows and demonstrate its capabilities in a 85-bus distribution network located at Steinkjer, Norway.

The rest of the paper is organized as follows. Section II, presents the multi-period alternating current OPF and the power system state estimator optimization models. Section III, presents the I3RES CIM profiles, whereas section IV presents the UML model, concrete and abstract classes of the I3RES profile. Section V briefly presents the middleware

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architecture and its services. Section V presents the results to illustrate the benefits of CPS approach. Conclusions and future directions of investigation are presented in Section VI.

2 MULTI-PERIOD ACOPF AND PSSE

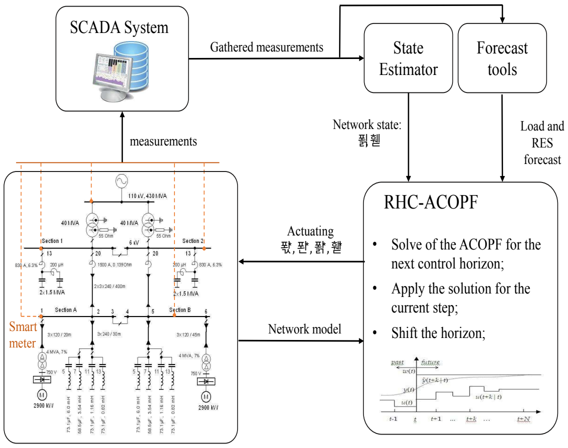

Fig. 1. Closed loop ACOPF

The RHC based OPF model captures the physical aspect of the network. The power flows are modelled using an AC network model with an pi equivalent circuit [9], a nonlinear and non-convex optimization problem. For closing the loop, the Alternating Current OPF (ACOPF) requires the network states and a simple power system state estimator (PSSE) is used to this extent. The two applications, RHC based ACOPF and PSSE exchange information using the CIM data models.

2.1 RHC based Optimal Power Flow Formulation

The objective of the multi-period ACOPF is to optimize the operating costs/line losses while simultaneously meeting the operating and physical constraints of the network. The objective function is given by,

$$\begin{aligned} f^E(t) &= C_0(t) + \sum_{i=1}^{N} \left(C_i^g(t) + C_i^b(t) \right), && (1) \\ f^L(t) &= \sum_{(i,j)\in\mathcal{E}} P_{(i,j)}^{\text{loss}}(t) && (2) \end{aligned}$$

Given an initial SoC, $b_i(\hat{t})\ \ \forall i$ and forecast of load $P_i^d(t), Q_i^d(t)\ \ \forall i,\ \ t \in [\hat{t}, \hat{t}+H]$ and generation $P_i^r(t), Q_i^r(t)\ \forall i,\ t \in [\hat{t}, \hat{t}+H]$ for each time step $\hat{t}$, the RH based controller computes the optimal input sequence $\mathcal{U}^{\hat{t}} = \left(U_1^{\hat{t}}, U_2^{\hat{t}}, \ldots, U_H^{\hat{t}} \right)$, where

$$U_t^{\hat{t}} = \left(P_i^g(\hat{t}+t), Q_i^g(\hat{t}+t), V_i(\hat{t}+t), \theta_i(\hat{t}+t), r_i(\hat{t}+t) \right), \tag{3}$$

is obtained by solving the finite-horizon optimal control problem:

$$\begin{aligned} &\min_{\mathcal{U}^{\hat{t}}} \sum_{t=\hat{t}}^{\hat{t}+H} f(t) \\ &\text{s. t.} \\ &P_{ij}(t) = \text{Re}(V_i^2(t) y_{ii}^* + V_i(t) V_j(t) e^{\mathrm{j}\theta_{ij}(t)} y_{ij}^*),\ \forall (i,j) \in \mathcal{E}, \forall t, \\ &Q_{ij}(t) = \text{Im}(V_i^2(t) y_{ii}^* + V_i(t) V_j(t) e^{\mathrm{j}\theta_{ij}(t)} y_{ij}^*),\ \forall (i,j) \in \mathcal{E}, \forall t, \\ &P_i^g(t) + P_i^r(t) - \sum_{j\in\mathcal{N}_i} P_{ij}(t) + r_i(t) = P_i^d(t),\ \forall i, t, \\ &Q_i^g(t) + Q_i^r(t) - \sum_{j\in\mathcal{N}_i} Q_{ij}(t) = Q_i^d(t),\ \forall i, t, \\ &S_{ij}^2(t) = P_{ij}^2(t) + Q_{ij}^2(t) \le \overline{S}_{ij}^2,\ \forall (i,j) \in \mathcal{E}, \forall t, \\ &b_i(t) = b_i(t-1) - r_i(t) - r_i^{\text{loss}},\ \forall i, t, \\ &-r_i^{\text{rated}} \le r_i(t) \le r_i^{\text{rated}},\ \forall i, t, \\ &\underline{B}_i \le b_i(t) \le \overline{B}_i,\ \forall i, t, \\ &\underline{P}_i^g \le P_i^g(t) \le \overline{P}_i^g,\ \ \underline{Q}_i^g \le Q_i^g(t) \le \overline{Q}_i^g,\ \forall i, t, \\ &\underline{V}_i \le V_i(t) \le \overline{V}_i,\quad \underline{\theta}_i \le \theta_i(t) \le \overline{\theta}_i,\ \forall i, t. \end{aligned} \tag{4}$$

The objective of ACOPF can be either to reduce the generation cost (1) or line-losses (2), or a weighted sum of both. The ACOPF formulation has the following constraints: power-flow, power balance, physical limits on the complex power injections, storage dynamics, charging rate constraints, storage capacity, generation limits, voltage magnitudes and load angles, respectively. The formulation extends the ACOPF model considered in [9] by adding the constraints on charging rate $-r_i^{\text{rated}} \le r_i(t) \le r_i^{\text{rated}}$, inclusion of the storage loss term r_i^{loss}, limits on the complex power injections $S_{ij}^2(t) = P_{ij}^2(t) + Q_{ij}^2(t) \le \overline{S}_{ij}^2$ and generator limits on real and reactive power generation $\underline{P}_i^g \le P_i^g(t) \le \overline{P}_i^g,\ \ \underline{Q}_i^g \le Q_i^g(t) \le \overline{Q}_i^g$. One can observe that the power flow constraints are non-linear and non-convex. Moreover, the presence of time-coupled dynamics of storage and fluctuating generation from renewable requires techniques handling time-dependencies. While multi-period OPF has been used to this extent, they lack capabilities to integrate forecast information and feedback after having applied the optimal decisions. Receding Horizon Control (RHC) overcomes this shortcoming by recomputing the optimal decisions during each time-instant. To deal with this complexity, convex relaxation techniques have been used in the literature with the underlying assumption that the line resistance is lesser than the reactance [21]. Usually, this assumption does not hold for distribution and microgrids wherein the line resistance is usually high. Therefore, the nonlinear, nonconvex and multi-step problem needs to be solved directly. This investigation uses the interior point method to solve the OPF thereby making the approach applicable to a wider class of electric networks than the ones studied in the literature. Though there are no guarantees on global optimality, the method provides faster solution that convex relaxation techniques.

The working of the RHC based ACOPF is shown in Fig. 1. Departing from the existing works in literature, the RHC based OPF in (4) includes forecasts on renewable generation and demand within the optimization model. Further, the proposed approach compensates for the disturbances and forecast errors. To this extent, the optimization model in (4) is solved at time instant $\hat{t}$ for a control horizon of H, then only the control inputs at time $\hat{t}$ are applied to the distribution grid, whereas the other computed control inputs are discarded. As the time horizon shifts (i.e. $\hat{t} \leftarrow \hat{t}+1$), the computation is repeated with new measured and/or estimated state and new forecasted generation and load. This way the optimal feedback policy course corrects for the disturbances and forecast errors. The inclusion of forecasts provides intelligence to the OPF that makes optimization driven decisions to decide the generation from dispacthable generators and scheduling of storage devices (charging/discharging decisions).

2.2 Power System State Estimator Formulation

To implement ACOPF, the power grid needs to continuously monitor the system states and provide feedback to the RH controller. In practice, the measurements are corrupted by noise and at times data loss also occurs. To overcome these difficulties, PSSE provides the state estimates i.e., phase angles and bus voltages, by using the virtual and pseudo measurements [22]. The measurements from supervisory control and data acquisition (SCADA) systems and network information (e.g., transmission lines, transformers, shunt parameters) are used as inputs to the PSSE. In addition, there are: *i)* virtual measurements, data related to network constraints (e.g., zero net power injections at buses with no load or generation), and *ii)* pseudo measurements, predicted values to improve measurement redundancy for making the network fully observable (e.g., demand forecasts). The output of the PSSE algorithm is the network state $x \in \mathbb{C}^n$ from whom all the others network variables can be computed through the power flows equations and power balance constraints.

Consider the set of measurements contained in $z \in \mathbb{R}^m$, it can be expressed in terms of system states as follows:

$$z = h(x) + \epsilon \tag{5}$$

where $\epsilon \in \mathbb{R}^m$ denote the measurement error vector while $h^\top = [h_1(x), \ldots, h_m(x)]^\top$ is the vector of nonlinear function relating measurements z to the state vector x. The error ϵ_i is assumed to be i.i.d. normally distributed with zero mean and known variance σ_i, i.e. $\epsilon_i \sim N(0, \sigma_i)$ as in [22]. The maximum likelihood estimator (MLE) for the network states using measurement equation in (5) is the minimizer of the optimization problem

$$\min_x \sum_{i=1}^{m} \left(\frac{z_i - \mu_i(x)}{\sigma} \right)^2 \tag{6}$$

where $\mu_i(x)$ is the expected value of i-th measurement, that is $h_i(x)$. Let us define the residual of measurement i as $\xi_i = z_i - \mu_i(x)$, this leads to the minimization problem:

$$\begin{aligned} &\min_x \; J(x) = \xi^T W \xi && (7)\\ &\text{s.t.} \;\; z = h(x) + \xi && (8) \end{aligned}$$

where W is a diagonal matrix containing the weights of the measurements, $W_{ii} = \sigma_i^{-2}$. The formulation in (7) is called the weighted least squares problem in literature and is solved using conventional optimization tools.

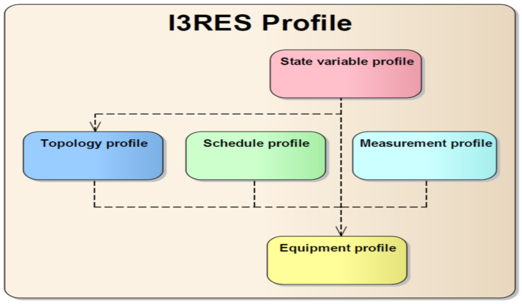

Fig. 2. I3RES Profile Description

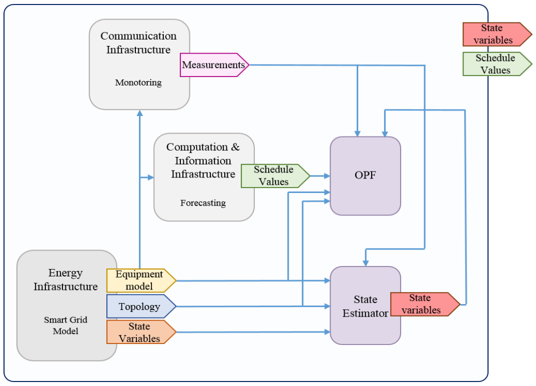

Fig. 3. Modularization in I3RES profile

3 CIM DATA MODEL FOR OPF AND PSSE

3.1 I3RES CIM profiles

The OPF and the PSSE are energy management applications that require information from heterogeneous devices in the distribution grid. Implementing OPF and PSSE needs transmitting network topologies (for modelling power flows), aggregate information from low-level devices, and data-exchange using semantics. Typically, SGs use middleware to aggregate information by providing interoperability and seamless connectivity. The CIM offers a standardized communication among different applications and devices and is defined in IEC 61970-301. It provides a semantic data model for describing various components of the power system at the electrical level. Furthermore, the IEC standard 61968-11 [23] extends semantic model of the IEC 61970-301 to include important definitions for distribution levels. Profiles are used to conceptually define information models and their relationships.

This section presents the *I3RES profile*, a subset of CIM profile that provides information models required for performing RHC based ACOPF and PSSE. The I3RES profile predefines the data-format, variable types, attributes and other details of the information model using relevant classes that are required for standardized communication among power system applications. The classes, attributes, and roles included in the standards IEC 61970-452 [24] and IEC 61970-456 [25] are chosen as the starting point for the profile implementation. The standard IEC 61970-452 provides the CIM base to facilitate applications for state estimation and power flow analysis.

3.1.1 I3RES Profile Structure

A modular design approach is used to develop the I3RES profile that in turn is divided into five profiles as illustrated

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in Fig. 2 with each of them addressing different components and usage of the network model. They are defined as:

- *Equipment profile* defines the physical equipment in the network such as lines, transformers, shunt capacitors, loads, generators and switches in the network. In general equipment rarely change, for instance only if the network is upgraded or if some other major changes are done in the equipment.
- *Schedule profile* is used to model schedules for both active and reactive power for generation and load, tap positions, and voltage regulation at generators and at equivalent injections.
- *Measurement profile* contains the measurement information (active and reactive power flows, bus voltages, branch currents, switch status, tap positions) needed by the state estimator application. This profile needs to be updated every time a new measurement data set is available from the SCADA system or any other measurement source. Note that generation and load forecast values are also modelled as measurements but with the *MeasurementValueSource* class indicating the specific source.
- *Topology profile* defines the classes needed to describe the network topology considering the status of the switches. The basic idea to build the topology is that the network equipment are connected to the same node on the topology provided there is no open switch between them. In the absence of switches, the network topology is fixed, whereas with switching action the network topology changes with time.
- *State variable profile* contains the model for defining the state variables of the network (e.g., bus voltage magnitude and phase angles, and active and reactive power flows). The output of the state estimator will use this model; consequently the data will be updated every time this tool produces a solution.

The relationship among these profiles is shown in Fig. 2. The profile connected at the “from” end of the arrows depends on the profile connected at the “to” end of the same arrow. Modularization of the I3RES profile is illustrated in Fig. 3. The rounded rectangles represent the outcome from the cooperating tasks (e.g., forecasting, monitoring and control services). In this setup, communication is fundamental to achieve the common goal. Thus, the CIM plays an important role to define a common abstraction level wherein all applications can exchange relevant information about the grid. In addition, the pentagons symbolize datasets that are described by the different profiles. The datasets are output from the associated application. The arrows show the information flow among the applications.

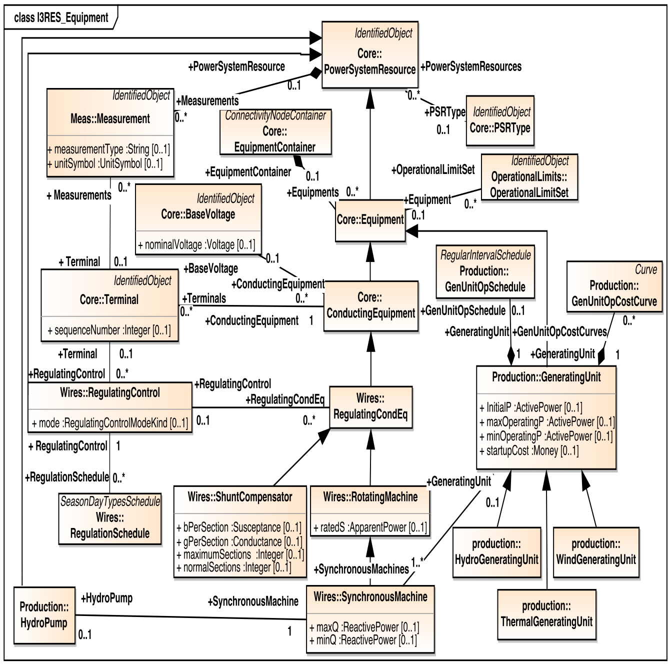

Fig. 4. Equipment Profile

The smart grid model provides information about the physical equipment contained in the network, the topology, and the state variables. The monitoring infrastructure takes as input the equipment measurement model and produces new measurements. The network state estimator uses the equipment model, the measurements, and the network topology as input and produces the state estimate. This is expressed as a state variable data set. The production and consumption prediction application gives a prediction schedule for production and load expressed as a schedule values data set, important for the OPF and state estimator algorithms. The optimal power flow application takes as input the result from the state estimation, the equipment model, the state variables, and the predicted schedule. Finally, the EMS produces an optimal solution expressed as a schedule and state variables data set, that can be shown to the end-user interfacing with the application infrastructure of the service-oriented architecture.

4 COMPONENT LIBRARY

The common information model is described in the Unified Modeling Language. This section provides the UML diagrams and the description of the component library in the I3RES Profile. Classes, attributes, and relationships are listed and discussed. In what follows, we present a detailed discussion of these profiles.

4.1 Equipment Profile

The objective of the *Equipment profile* is to model the network equipment such as lines, transformers, shunt capacitors, loads, generators and switching elements, to name a few. Switching elements are not strictly required if the topology is considered fixed. The *Equipment profile* is defined in part IEC 6197-452 and its instances are almost always static and change only if some network equipment is added, removed or its electrical characteristics are changed. Information related to topology, load and generation schedules, measurements, regulating schedules, topology and state variables are handled by other profiles. Fig. 4 shows the *Equipment profile* class along with contained subclasses, inheritance, dependencies, and their relationships. The *Equipment profile* is a meta model that contains the classes *Equipment* and *ConductingEquipment*, whose inherited classes are:

- A subset of the *Equipment Profile* classes is shown in Fig. 5. Here the class *ACLineSegment* is used to model the bus line/distribution segment. This class inherits

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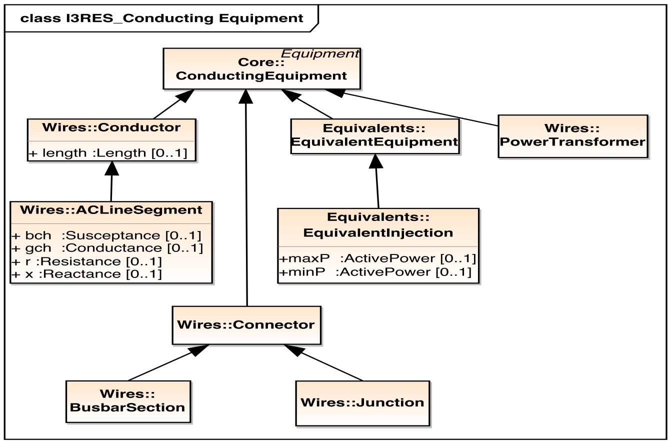

Fig. 5. Conducting Equipment sub-set of *Equipment profile*

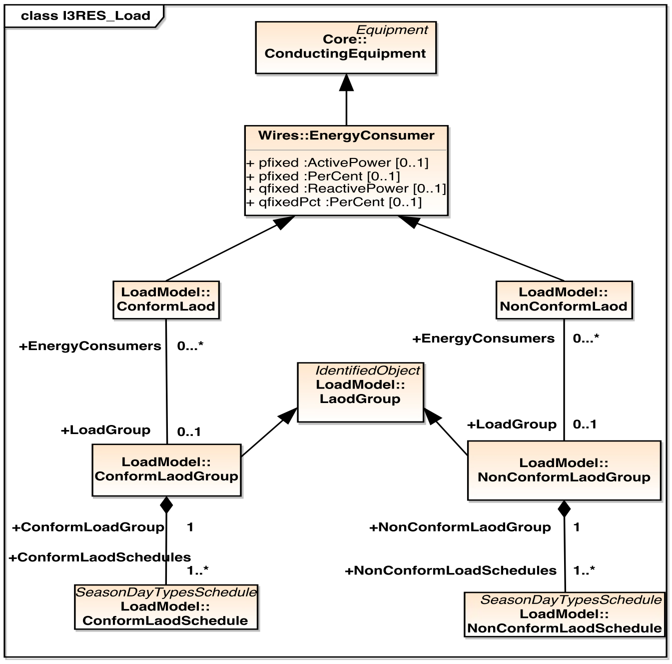

Fig. 6. UML model of the Load

from the class *Conductor*, which in turn inherits from the class *ConductingEquipment*.

- The subset of *Equipment profile* classes that model a load are shown in Fig. 6. The load class inherits from the *ConductingEquipment* shown in Fig. 5. The load may be specified as conform or non-conform load. The difference between the two lies in the corresponding load schedule.
- The classes required to model the power transformer are modelled using the class *I3RESPowerTransformer* in the *I3RES Profile*. Notice that a *TapChanger* class is available and may be applied to model possible tap changers necessary to change the transformer voltage.
- The equipment operating limits are described using the classes shown in Fig. 7. For example, the voltage limits are specified using the *VoltageLimit* class. The container class consists of group of different type of equipment grouped together. Depending on the size of the container, the *SubgraphicalRegion* and *GeographicalRegion* classes are used to define the sector/area in which different types of equipment in the same group are contained.

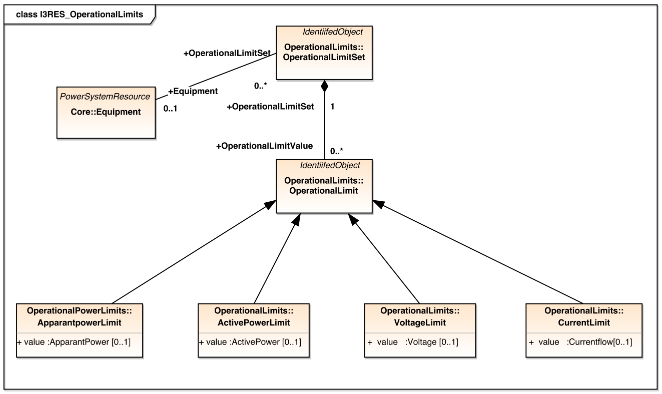

Fig. 7. Operational limits of typical equipment class

4.1.1 Concrete Class

1) An *ACLineSegment* is a wire or combination of wires, with consistent electric characteristics, used in building an electric system. It is used to carry alternating current between points in the power system. The impedences and admittances required for modelling the network in ACOPF is obtained from this class. The class *ACLineSegment* has two terminals and a *Terminal* class defines the connecting terminals. Each connection defines two *Terminal* instances. Thus, this models the connectivity between the buses and nodes in a distribution network, whereas the connectivity of each terminal is given by the *Topology profile* model. Operating limits of the line are given by the *OperationLimitSet* class that contains the active and reactive power, current and voltage of the line pointing to the *ACLineSegment* class.
2) *ActivePowerLimit* class specifies the limit on active power flow. The operating limit points to the *OperationalLimitSet* class that points to the equipment to which the limit applies.
3) *ApparentPowerLimit* classes specify the apparent power limit which is an operational constraint in the ACOPF problem. The operational limit points to the *OperationalLimitSet* class that points to the equipment to which the limit applies.
4) *Breaker* is a mechanical switching device capable of making, carrying and breaking currents under normal circuit operation. During abnormal conditions, it is capable of making, carrying for a specified time and breaking currents under specified abnormal circuit conditions, e.g., during short-circuits.
5) *BusbarSection* describes a conductor or group of conductors, with negligible impedence, used to connect other conducting equipment within a single substation. Voltage measurements are typically obtained from *VoltageTransformers* that are connected to bus bar section modelled as one

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logical terminal. A *BusbarSection* is contained by a *VoltageLevel* in a substation.

6) *ConformLoad* class represents loads that follow a daily load change pattern, where the pattern can be used to scale the load with a system load. The load can be described in two ways:
    - using a fixed active and reactive power consumption (setting the *pfixed* and *qfixed* attributes);
    - using the link to *ConformLoadGroup* together with *ComforLoadGroupSchedule* class in the Schedule profile and the *pfixedPct* and *qfixedPct* indicating the load schedule percentage taken by the *ConformLoad* instance.
7) The connectivity nodes defined by the class *ConnectivityNode*, are points where conducting equipment terminals are connected together with zero impedance. The network topology will depend on the status of the switches, so that the *TopologicalNode*, in the *Topology* profile, represents the bus concept used to build the branch flow model of the power network.
8) The *CurrentLimit* class specifies the operational limit on the branch current. The operational limit points to the *OperationalLimitSet* class that points to the equipment to which the limit applies.
9) Generating units are represented using the class *GeneratingUnit* which represents a single or a set of synchronous machines for converting mechanical power into alternating-current power. For example, individual machines within a set may be defined for scheduling purposes while a single control signal is derived for the set. In this case there would be a *GeneratingUnit* for each member of the set and an additional *GeneratingUnit* corresponding to the set. *GeneratingUnit* is, together with *SynchronousMachine* and *PSRType* classes, used for modelling any kind of generators, included distributed energy resources and storage systems. If the generator contains a generation schedule, this is described with *GenOpSchedule* class in Schedule profile. The generator unit operating costs are described using the *GenOpCostCurve* class.
10) *GeographicalRegion* describes a geographical region of a power system network model and must contain at least one *SubGeographicalRegion*.
11) *GeographicalRegion* describes a geographical region of a power system network model. A GeographicalRegion must contain at least one *SubGeographicalRegion*.
12) *Junction* describes a point where one or more conducting equipment are connected with zero resistance. A Junction is contained by a VoltageLevel in a Substation or a Line.
13) *Line* contains equipment beyond a substation belonging to a power transmission line. A Line belongs to a *SubGeographicalArea* and contains *ACLineSegement* elements.
14) *LoadBreakSwitch* is a mechanical switching device capable of making, carrying, and breaking currents under normal operating conditions.
15) *NonConformLoad* represents loads that do not follow a daily load change pattern and changes are not correlated with the daily load change pattern. The load can be described in two ways:
    - using a fixed active and reactive power consumption (setting the *pfixed* and *qfixed* attributes);
    - using the link to *NonConformLoadGroup* together with *NonComforLoadGroup-Schedule classes*, in the Schedule profile, and the *pfixedPct* and *qfixedPct* indicating the load schedule percentage taken by the *ConformLoad* instance.

The other concrete classes defined in the model include *OperationalLimitSet*, *PowerTransformer*, *PSRType*, *RatioTapChanger*, *Recloser*, *ShuntCompensator*, *SubGeographicalRegion*, *Substation*, *SynchronousMachine*, *Terminal*, *ThermalGeneratingUnit*, *WindGeneratingUnit*, *PowerTransformerEnd*, *NonConformLoadGroup*, *GenUnitOpCostCurve*, *VoltageLevel*, *VoltageLimit* and *HydroGeneratingUnit*.

4.1.2 Abstract Classes

The abstract classes of the *Equipment profile* are described briefly.

1) *BaseVoltage* defines a system base voltage.
2) *ConductingEquipment* includes the parts of the power system that are designed to carry current or that are conductively connected through terminals.
3) *Conductor* is a combination of conducting material with consistent electrical characteristics, building a single electrical system, used to carry current between points in the power system.
4) *ConnectivityNodeContainer* is a base class for all objects that may contain connectivity nodes or topological nodes.
5) *Connector* represents a conductor, or group of conductors, with negligible impedance, that serve to connect other conducting equipment within a single substation and are modeled with a single logical terminal.

The other abstract classes are *Curve, EnergyConsumer, Equipment, EquipmentContainer, EquivalentEquipment, IdentifiedObject, LoadGroup, OperationalLimit, PowerSystemResource, ProtectedSwitch, RegulatingCondEq, RotatingMachine, Switch, TapChanger and TransformerEnd*

4.2 Schedule Profile

This profile is used for modeling schedules for active and reactive power generation and load, tap positions, and voltage regulation at generators and at equivalent injections. The classes contain information to represent the active and reactive power injections, voltage, and transformer tap position over time. The types of equipment to which the schedules refer are given in the *Equipment profile*.

4.3 Measurement Profile

This profile is used for modeling measurement data needed by the state estimator tool and allows for modeling active and reactive power, current and voltage measurements. Also discrete measurements are modelled for indicating the status of switching elements, tap positions and shunt compensator bank connections. Note that measurements

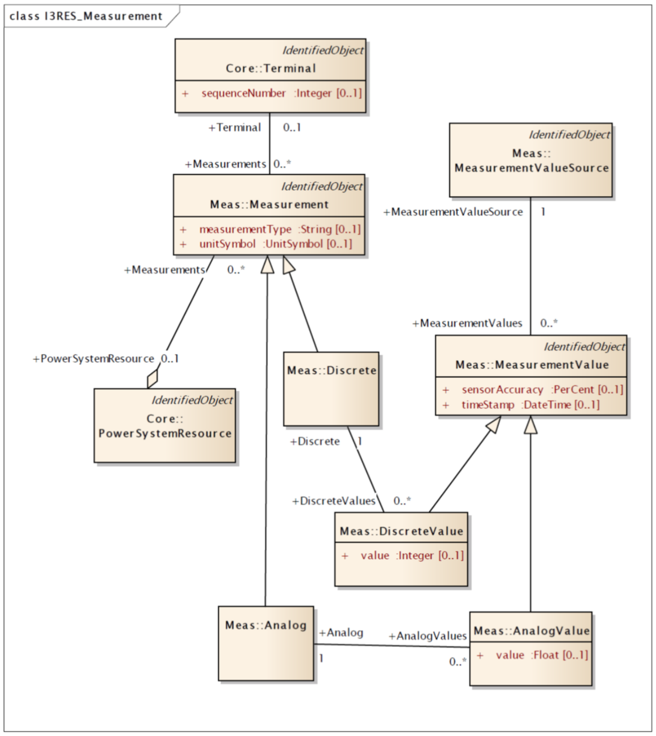


Fig. 8. Measurement profile

may have different sources, coming from the SCADA system, generation forecasting or load forecasting. Note also that schedules are not used as input to the state estimator since they lack the required information such as the accuracy value. If generation schedules or load profiles will be used as input for the state estimator these need to be given in form of measurements to the state estimator indicating the value source as ”forecasted”. Fig. 8 models the measurement profile and shows its relationship with the *Equipment profile*.

4.3.1 Concrete Classes

1) *Analog* represents an analog measurement. The type of measurement can be a branch current, an apparent power, a bus voltage, an active or reactive power injection, etc. The *Analog* measurement needs to point to the *Terminal* which is the source of measurement value .
2) *AnalogValue* represents an analog *MeasurementValue* linked to a measurement point through the Analog attribute. The *MeasurementValueSource* attribute indicates the source of the measurement, e.g., a SCADA system.
3) *Discrete* represents a discrete measurement, i.e., a measurement representing discrete values, e.g., a breaker position. The type of measurement can be a tap or a switch position, etc. The discrete measurement needs to point to the *PowerSystemResource* to which the measurement value applies.
4) *DiscreteValue* represents a discrete *MeasurementValue*. *DiscreteValue* is linked to a measurement point through the Discrete attribute. The *MeasurementValueSource* attribute indicates the source of the measurement.
5) *MeasurementValueSource* describes the alternative sources updating a *MeasurementValue*. User conventions for how to use the *MeasurementValueSource* attributes are described in the introduction to IEC 61970-301 standard. *MeasurementValueSource* indicates the source of the measured value.

4.3.2 Abstract Classes

1) *IdentifiedObject* is root class to provide common identification for all classes needing identification and naming attributes.
2) *Measurement* represents any measured, calculated or non-measured and non-calculated quantity. Any piece of equipment may contain measurements, e.g., a substation may have temperature measurements and door open indications, a transformer may have oil temperature and tank pressure measurements, a bay may contain a number of power flow measurements and a breaker may contain a switch status measurement. The *PSR - Measurement* association is intended to capture this use of *Measurement* and is included in the naming hierarchy based on *EquipmentContainer*. The naming hierarchy typically has Measurements as leaves, e.g., *Substation-VoltageLevel -Bay- Switch-Measurement*.
3) *MeasurementValue* represents the current state for a measurement. A state value is an instance of a measurement from a specific source. Measurements can be associated with many state values, each representing a different source for the measurement.

4.4 Topology Profile

This profile defines the classes needed to describe the network topology that describes how each equipment in the network is electrically connected to each other. Topology is given by the association of buses (topological nodes) with the corresponding association to the terminals of equipment. This way the network model is built as a branch flow model that can be directly used by the ACOPF or PSSE tools. If the network topology is fixed, the topology data can be pre-calculated and the corresponding OPF and state estimation tools can use this data directly. On the other hand, if the topology of the network is dynamic the topology configuration is computed based on the switches and their statuses indicated by their discrete measurement values. Figure 9 models the Topology profile and shows its relationship to the *Equipment profile*.

4.4.1 Concrete Classes

1) To obtain a detailed substation model a *TopologicalNode* is a set of connectivity nodes that, in the current network state, are connected together through any type of closed switches, including jumpers. Topological nodes change as the current network state changes (i.e., switches or breakers change state). For a planning model, switch statuses are not used to form topological nodes. Instead they are manually created or deleted in a model builder tool. Topological nodes maintained this way are also called ”buses”. The terminals to which each *TopologicalNode* is connected are linked to the *Equipment profile*.

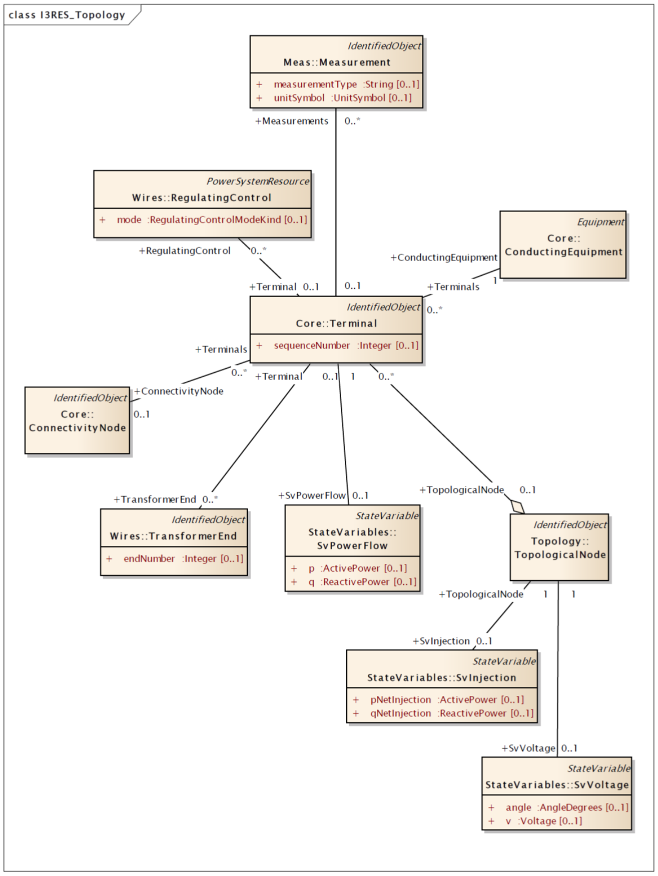


Fig. 9. Topology profile

4.4.2 Abstract Classes

1) *IdentifiedObject* is a root class to provide common identification for all classes needing identification and naming attributes.

4.5 State Variable Profile

This profile defines the classes needed to describe the results of the state estimator and power flow tools. The main state variables are the voltage magnitude and phase angles at every bus (*TopologicalNode*) in the network. Knowing them, the rest of the derived state variables can be calculated. These are: active power and reactive power flows over branches and transformers, and active power and reactive power injections at every bus. Other state variables are also supported such as tap positions, shunt compensator, and switching elements. Fig 10 models the *State variable profile* and shows its relationship to the *Topology* and the *Equipment profile*.

4.5.1 Concrete Classes

1) *SvInjection* is the injection state variable and it is used for addressing situations where exchanged models have Kirchhoff's law mismatch at a bus. This includes exchange of partial models with boundary flows and state estimator solutions with residual mismatch. *SvInjection* describes the calculated active and reactive power injections at each bus (*TopologicalNode*). This class points to the corresponding *TopologicalNode* in the *Topology profile*. Positive values are considered as injections going into the node while negative values are considered withdrawals going out of the node.

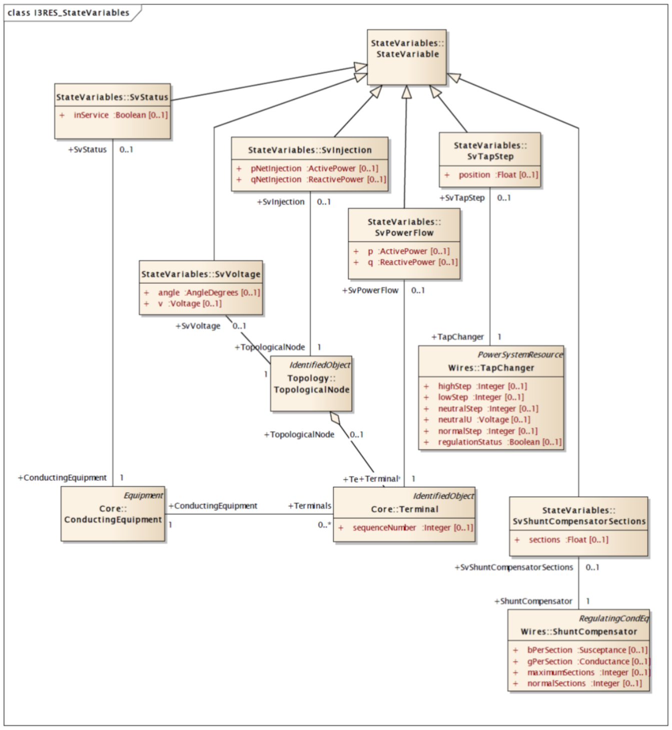


Fig. 10. State Variable profile

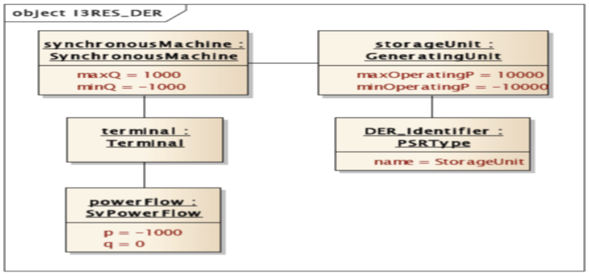
2) *SvPowerFlow* This class is the state variable for power flow. Load convention is used for flow direction. This means flow out from the *TopologicalNode* into the equipment is positive. *SvPowerFlow* describes the calculated active and reactive power flows over conducting equipment in the network. This class points to the corresponding *Terminal* in the *Equipment profile*.
3) *SvShuntCompensatorSections* is the state variable for the number of sections in service for a shunt compensator. The shunt to which the state variable applies is given in the *Equipment profile*.
4) *SvTapStep* is the state variable for transformer tap step. This class is to be used for taps of load tap changing (LTC) transformers, not fixed tap transformers. Normally, a profile specifies only one of the attributes position or *tapRatio*. The *TapChanger* to which the state variable applies is given in the *Equipment profile*.
5) *SvVoltage* is the state variable for voltage. This class indicates calculated voltage magnitude and phase angle for every bus in the network. The bus is given by the *TopologicalNode* in the *Topology profile*.

4.5.2 Abstract Classes

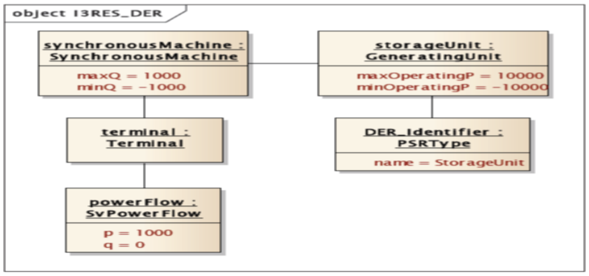
1) *StateVariable* and *SvStatus* represented the abstract class for state variable and its status.

4.6 Renewable Energy Sources Library

The ACOPF needs model of the RES, such as solar photovoltaics, energy storage systems and wind/hydro turbines. Some RES sources can both produce and consume



(a) Storage unit discharging mode.



(b) Storage unit charging mode.

Fig. 11. Runtime Instance of Storage Unit and RES

energy. Currently, CIM profiles supporting them are not available. The general philosophy of CIM standard is to develop new classes for equipment/objects that are not yet defined. For instance, the missing RES could be modeled by extending the CIM with new classes for each RES type. As the new classes would not be supported by existing CIM tools, this approach is not used in this investigation.

To model RES, *GeneratingUnit* and *SynchronousMachine* classes that do not give specific information about the technology being used (PV, wind/hydro turbines, energy storage units etc.), but they have sufficient details to implement the ACOPF and PSSE. The *GeneratingUnit* class has the information about the active power of the generator while the *SynchronousMachine* class is focused on the reactive power and the connection of the generator to the grid. In addition to these classes, the PSRType class is also used to classify instances of the same class and provide customization that is non-standard in CIM. With this approach, the RES is modelled using *GeneratingUnit* and *SynchronousMachine* with negative power values when supplying power to the grid and with positive value when consuming or storing energy, while the *PSRType* class adds information about the type of RES. Fig. 11 shows an example of storage unit runtime instance that represents the discharging and charging mode.

5 CIM ENABLED SEMANTIC MIDDLEWARE

This section presents a succinct description of the middleware giving a brief overview of the services and integration with the energy grids. Further, it demonstrates the need for semantic information model for the middleware. The field level sensors in the electric grid are interfaced to the SCADA using the vendor specific network protocols. A communication infrastructure is implemented that takes the data from the SCADA system and uses the AMQP (Advanced Message Queuing Protocol) to store the data in a real-time database. Then a middleware is used to transform this information from lower level devices into the one suitable for third party applications such as the OPF and PSSE. The CIM data model described in the previous section, i.e., the *I3RES Profile* provides a standardized data model for transferring data among the different layers of the middleware as well as with other application.

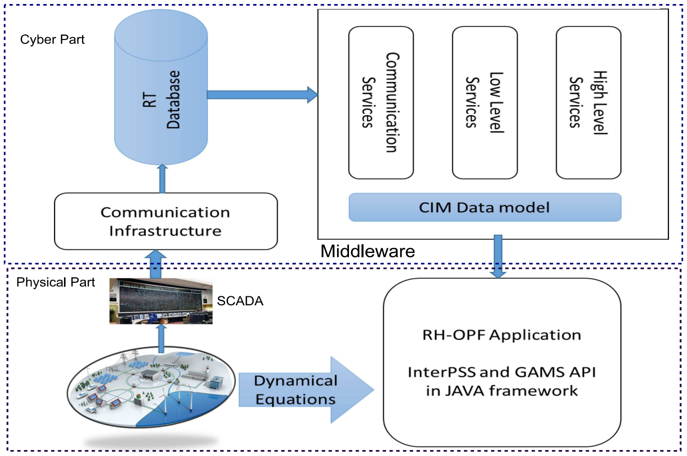


Fig. 12. CPES Approach for OPF

The middleware is composed of lower, higher, and communication layers that provide services for third party applications to access grid data. The communication layer has the *Information Harvest* service that provides mechanisms to obtain data for a particular service within the middleware. In addition, it performs data conversion for the other services. The lower level services connect the hardware communication layer and the layer providing higher level services. This layer has the following important services: *Service Discovery*, and *Data Management*. The higher level services layer has the services required for applications such as Inner Information Harvest that provides data required for specific applications, Outer Information Harvest, which provides access to the data available from external sources, such as weather forecast, energy pricing services, etc., and finally the ancillary services required for a specific applications such as the OPF. Using the middleware the third party control applications can take information from the lower level devices as shown in Fig. 12.

In the RH-ACOPF and PSSE implementation, the CIM model are used for: *(i)* obtaining network topology and detect changes, *(ii)* standardized information exchange for heterogeneous field devices to energy management applications, *(iii)* information exchange among third-party applications, and *(iv)* provide semantic capabilities to the data through use of ontology. Solving RHC based ACOPF and PSSE requires network information for calculating line-flows which depend on the network topology. The CIM captures the network topology using XML format, this data is serialized using Resource Document Format (RDF) that denotes the link between two elements in an electric network. The RDF is the language for expressing the metadata that can be interpreted by the different services of the middleware and third party energy management applications such as the OPF. In the proposed OPF and PSSE implementation, the RDF schema is converted to network topology by using the application program interface (API) of InterPSS, a software that captures the network topology. The middleware transmits the RDF schema in XML formats for modelling the topology. Any changes in the network

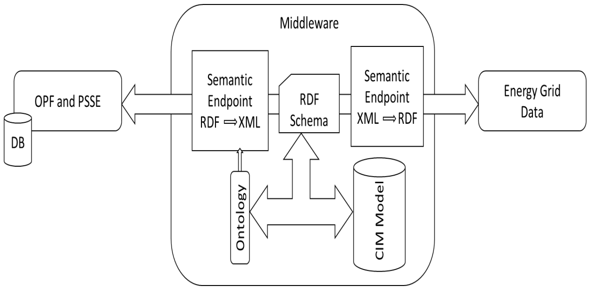


Fig. 13. CIM Integration with the Middleware Using Ontology

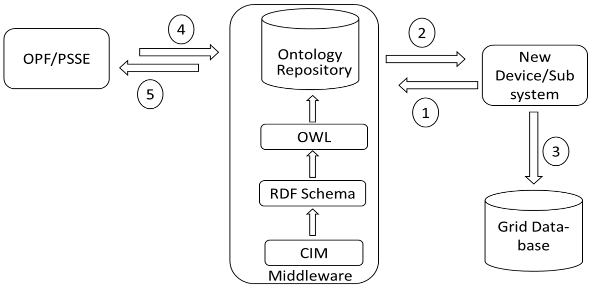


Fig. 14. Working Sequence of the Ontology

such as change of components is detected using the services of the middleware, e.g., device discovery, and the RDF schema is updated. Thus the changes in network topology or components are reflected back into the OPF and PSSE application.

Second, the CIM provides a standardized format for data exchange between field devices and other applications of the EMS. The measurements from heterogeneous devices are aggregated using the services of the middleware and transformed into XML format by translating the RDF schema or any other format. The CIM defines the data structure, variables, data types, and other aspects of the data to be exchanged between the devices and the energy management applications, OPF and PSEE. To this extent, it uses the semantic end-point as shown in Fig. 13, that translate XML to RDF or vice-versa. The semantic endpoints also translate the data in any other format or web applications into XML format. Therefore, the CIM provides a standardized way to update measurements from the grid to any other energy management applications including the OPF and PSSE.

Third, the OPF implementation requires forecast information on demand and renewable generation and the estimates of the network state to correct the measurement errors and noise. The forecast and the PSSE are usually developed as third-party EMS applications that provide OPF with the required information. The CIM provides a standardized way to exchange information among these different applications and also among different layers of the middleware.

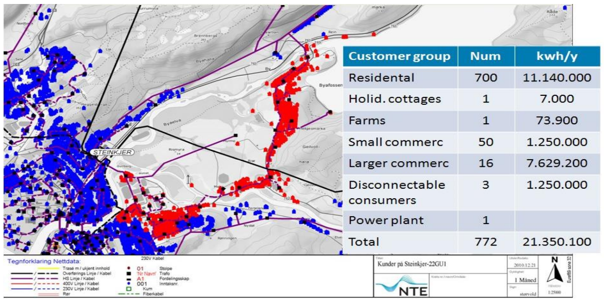
Fourth, the CIM provides semantic capabilities to the middleware that helps it organize information for different applications and takes actions based on aggregated information. Thus, the capabilities of the middleware are enriched using the CIM. This is performed by using ontologies, a description of the entities pertaining to a particular domain (e.g., components of an electric network), formally described along with their relations organized hierarchically. The ontology thus is a smart dictionary that connects the middleware components to the data models (called I3RES data models) that are provided by the CIM model described in the previous section. Three components interoperate using the middleware: the OPF and PSSE application, the semantic data base and the semantic information model through use of CIM. By using these components the middleware organizes the data required for the particular application, e.g., OPF. In our EMS, a JAVA framework was used to develop the OPF and PSSE. They aggregated network topology and data employing XML format using CIM based standardized exchanges via the InterPSS API. The GAMS (Generic Algebraic Modelling System) APIs were used to solve the OPF problem using the IPOPT solver. In addition the CIM provided data models to exchange data with the forecasting tool and the PSSE. They were integrated using an API wherein the XML schema updated the information. The OPF are solved in the software framework and the results are published in CIM format as well for providing user interface.

Computationally, it has an ontology subsystem that is responsible for formatting all the data being transferred to the representation style called the *Formatter*. Further, there is another component called the *Updater* that updates the ontology, when a new service or device is being added. Finally, there is the repository sub-system that is primarily used for ontology storage. The working sequence of ontology is shown in Fig. 14: whenever a device/subsystem is added to the SG, a request is sent to the middleware for the data model to be used (1). The data representation format is returned based on the CIM which involves different features (units, thresholds etc.) (2) and this gets stored in the data repository (3). For the OPF, the information on power production, consumption, energy costs, power flows and locations will be mapped to the ontology that are described using OWL (ontology web language) and they are combined with the RDF schema from CIM to represent different ontologies. Consequently, semantically annotated data are produced that matches an ontology. Whenever the OPF or the PSSE application requests data, the ontology repository provides the data using the services of the middleware.

Traditional point-to-point connections requires that the information be tailored for the specific application and made available as APIs for each of them. However, with the CIM based communication, multiple applications receive the same data simultaneously. In addition, data models from different vendors are standardized into a single model which reduces cost for developing a metadata repository as the master source. With this approach, the utilities can reduce the time, cost and effort for creating data models for different vendors and through the use of semantic capabilities enhance the intelligence of the middleware. In other words, CIM provides a standardized interface for designing flexible energy management systems for power grids. Thus the CPS approach shown in Fig. 12 enables more flexible EMS for energy grids.

6 CASE STUDY

The distribution grid studied for implementing multi-period ACOPF and PSSE is the Demo Steinkjer, Norway



Customer group	Num	kwh/y
Residental	700	11.140.000
Holid. cottages	1	7.000
Farms	1	73.900
Small commerc	50	1.250.000
Larger commerc	16	7.629.200
Disconnectable consumers	3	1.250.000
Power plant	1	
Total	772	21.350.100

Fig. 15. Case Study: Demo Steinkjer network in Norway

shown in Fig. 15 ; a demonstration pilot for the EU FP7 project I3RES. It is a radial bus network that consists of: a hydro power plants with 2 generators, 32 aggregating loads, 50 link buses (i.e., without generation nor load) and 84 transmission lines. The RES (other than the hydro generators) and ESS are currently not available in the distribution network, and are therefore simulated.

6.1 Network Model

The CIM defines a basic ontology, that is, a hierarchy of concepts and relationships within a domain described through a set of attribute-value pairs. Ontologies are often written in XML or in a Resource Document Framework (RDF), which represent a suitable file format for effectively exchanging information at the middleware level in a service-oriented platform, through a common communication bus.

The CIM standard specifies in the IEC 61970-552 [26] how the description of a network model can be serialized using the RDF schema, an XML format that allows defining relationships between attribute-value XML pairs. The main concept in RDF is called triple and consists of a subject-predicate-object expression, where a given resource (subject) has a relationship (predicate) with another resource (object). An RDF document contains elements that are identified by a unique ID attribute and that can be referenced from other elements by using that ID in a resource attribute. Using this approach, RDF provides the means to map an object oriented design to XML so it is perfectly suited to map CIM class structure and relationships into XML.

The I3RES CIM Profile can be represented as RDF schema documents. In details, once having selected all the classes, attributes and relationships among classes (inheritance, aggregation, cardinality, etc.), there exist tools (e.g., the CIMTool) that allow developing the RDF schema corresponding to the elements included in the profiles. The code in listing Appendix A.1 is an example of the RDF schema for the power line definition through the *ACLineSegment* class, whose attributes are given as independent resources as shown in Appendix A.2. An RDF serialization for a power line instance is shown in Appendix A.3, where it can be seen how the values of the different attributes are assigned.

6.2 ACOPF Results

The proposed ACOPF with RES and ESS was implemented as a service using the CIM data models and SOA middleware. To test the working, a sampling time of one hour and prediction horizon of 24 hours are considered. Tests are performed over a day using forecast and PSSE. The parameters and conditions associated with the generators and the PCC are given in Table 1, whereas the linear cost coefficient for storage unit is equal to 0.1 €/MWh. The cost of power purchased/sold from/to the main grid through the PCC [1]. The voltage magnitude limits for all buses are set to $0.95 \leq |V_i| \leq 1.05$ pu and the phase shift between the connected buses is set to 10^o. Each transmission line has a maximum apparent power $S_{ij}^{\max} = 7.2$ MVA. The storage is limited by a capacity of 4 MWh with the maximum and minimum charge or discharge power rate equal to 1 MW and a storage loss of 0.01 MWh.

Unit	S_{min} [MVA]	S_{max} [MVA]	c^g [€/MWh]	c^S [€/MWh]	c^P [€/MWh]
Hydro 1	0	1.6	20	0	0
Hydro 2	0	1.0	20	0	0
PCC	0	4	0	30	160

TABLE 1
Test Parameters of Steinkjer Network

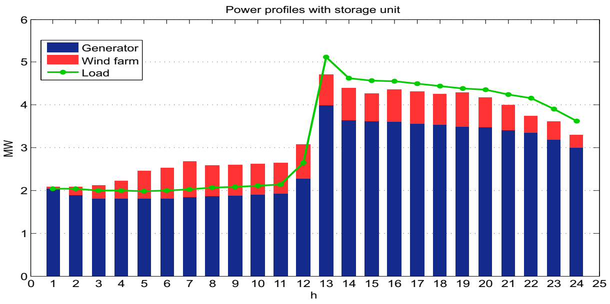


Fig. 16. Generation Planning with Storage

The multi-period ACOPF is implemented using the proposed CIM model and SOA based middleware integrating energy storage systems and renewable generation. Fig. 16 shows the advantages of using ESS; the storage units avoid peaks by reducing the cost value by 14.6 %. The storage profile shown in Fig. 17 illustrates the role of storage systems in reducing the generation cost.

During periods when the power demand is low, the hydro units can sell the surplus power to the grid (see Fig. 18 from 1 am to 12 pm); during other periods power is purchased from the utility. Comparison of Fig. 16 and Fig. 18 reveals that the operating costs of the grid are reduced due to reduction of power purchased from the utility grid during periods when the renewable generation meets the grid requirements.

6.3 Performance

The ACOPF computation time was compared with the multi-period implementation. An average execution of the algorithm was 1.574 s, whereas the multi-period OPF solved using genetic algorithm the average execution time was about 4.7 minutes over 50 runs with 200 generations. Furthermore, the average deviations from the global optimal for a 24 hour horizon is about 2.6-3.12% of that computed with multi-period GA. The computations time and closeness to the global optimal solutions with the proposed ACOPF solution method suggests that the proposed implementation is more suitable for implementing the ACOPF in energy grids. Moreover, the implementation considers both cyber

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[1] http://www.ssb.no/en/energi-og-industri/statistikker/elkraftpris

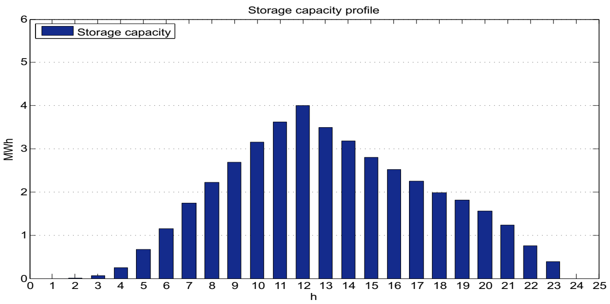

Fig. 17. Storage Profile on the Grid

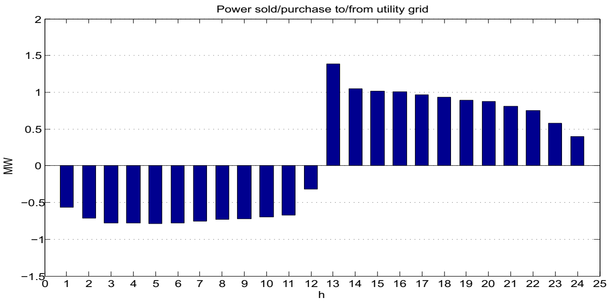

Fig. 18. Active Power Exchanged with the Utility Grid through the PCC bus

and physical aspects of the implementation, rather than only the physical aspects leading to more realistic solutions in scenarios envisaged in the grid.

7 CONCLUSION

This investigation presented a cyber-physical systems for implementing RHC based ACOPF in smart grids having intermittent renewable energy sources and energy storage devices. The RHC based ACOPF used forecast on demand RES, current network measurement and a simple power system state estimator to solve an ACOPF problem in a receding horizon manner. The use of RHC approach was used to deal with intermittencies and uncertainties. To solve the problems of interoperability and interaction with external entities a communication architecture was proposed. The common information model (CIM) provided an abstract and comprehensive data model that provides support for standardized information exchange for implementing multi-period ACOPF and PSSE. The CIM models the smart grid and provides a component library for modelling the power network. The CIM classes required to model RES, ESS and PSSE specific entities were modelled using the *I3RES profile*. The CIM extension provided by this investigation are important for information exchange among various applications in energy in the systems. As a result, different applications can require access to information through a common file format using the same communication bus supported by the middleware architecture. A middleware that builds on the CIM model and communication infrastructure to aggregated data from sensors was proposed. The CIM model together with the middleware modelled the cyber-part of the network. The proposed CPS approach was illustrated on an grid in Steinkjer, Norway. Our results bring out the advantages of using the CPS approach both as a modelling and engineering tool for smart grids. Extending to other EMPC applications and proposing a meta-model that captures the cyber and physical aspects of the network are future prospects of this investigation.

APPENDIX A
SERIALIZATION OF CIM PROFILES

A.1 Power line definition using the RDF schema

```
<rdf:Description rdf:about="#ACLineSegment">
  <rdfs:subClassOf rdf:resource="#Conductor"/>
  <cims:belongsToCategory rdf:resource=
    "#Package_Wires"/>
  <cims:stereotype rdf:resource="http://
    langdale.com.au/2005/UML#concrete"/>
  <rdfs:comment>A wire or combination of wires
  </rdfs:comment>
  <rdfs:label>ACLineSegment
  </rdfs:label>
  <rdf:type rdf:resource="http://
    www.w3.org/2000/01/rdf-schema#Class"/>
</rdf:Description>
```

A.2 Definition attributes of a power line using the RDF schema

```
<rdf:Description rdf:about="#ACLineSegment.x">
  <cims:stereotype rdf:resource="http://
     langdale.com.au/2005/UML#attribute"/>
  <rdfs:comment>Positive sequence series
     reactance of the entire line section
  </rdfs:comment>
  <rdfs:label>x
  </rdfs:label>
  <cims:dataType rdf:resource="#Reactance"/>
  <rdfs:domain rdf:resource="#ACLineSegment"/>
  <cims:multiplicity
     rdf:resource="http://iec.ch/TC57/1999/
     rdf-schema-extensions-19990926#M:1"/>
  <rdf:type rdf:resource="http://
     www.w3.org/1999/02/22-rdf-syntax
     -ns#Property"/>
</rdf:Description>
```

A.3 Serialization of Power Line Instance

```
<cim:ACLineSegment rdf:ID="ACLS_256541">
  <cim:IdentifiedObject.name>ACLS_256541
  </cim:IdentifiedObject.name>
  <cim:ConductingEquipment.BaseVoltage
     rdf:resource="#BaseVoltage_2"/>
  <cim:ACLineSegment.bch>0.000422
  </cim:ACLineSegment.bch>
  <cim:ACLineSegment.gch>0
  </cim:ACLineSegment.gch>
  <cim:ACLineSegment.r>0.008611
  </cim:ACLineSegment.r>
  <cim:ACLineSegment.x>0.002055
  </cim:ACLineSegment.x>
</cim:ACLineSegment>
```

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