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Virtual Power Plant for Grid Services using IEC 61850

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***Abstract*— This paper assesses the communication, information and functional requirements of Virtual Power Plants (VPPs). A conceptual formulation of the interoperability requirements is presented as well as a comparative study of their fulfillment by state-of-the-art communication techniques. VPP requirements are then mapped against services and information models of IEC 61850 and CIM power utility automation standards. Proposals are given for extensions of the IEC 61850 standard to enhance the interaction between VPP controller and the distributed energy resources. Finally the methodology and concepts are applied to a specific VPP consisting of hydro and wind plants, solar PV and storage facilities. Several applications to provide grid services from the proposed VPP in an existing 50 kV grid are covered. The implementation of the VPP communication and control architecture in the SCADA of demonstration plant is also presented.**

***Index Terms*— Distributed power generation, Energy storage, Reactive power control, Virtual power plant**

I. Introduction

A Virtual Power Plant (VPP) is a term used for aggregation of Distributed Energy Resources (DER) in order to make them appear as a single, larger, power plant [1]. When the VPP also includes storage and demand response capabilities, it allows variable renewable energy sources, like wind and solar photovoltaic (PV) power, to act as a large dispatchable power plant.

Whereas the energy market participation of the VPP is obtained by the joined production of all the DER units, the interaction with the grid is different for each unit and dependent on their location in the grid. The grid will limit the ability of the VPP to participate in the electricity market. By providing grid services, the VPP allows the coordinated control of DER units that in turn enables for a higher proportion of variable energy production in the grid. The optimized control of multiple small units, possible within a VPP, can then reduce the burden on the remaining large power plants to stabilize the grid as their proportion of the total electricity production declines.

The integration costs for providing grid services is a major concern with diverse units that do not have a common ownership and that are from different manufacturers, each potentially using its own propriety communication interface. For a VPP to be cost effective in integrating a broad variety of DER units, standardized communication interfaces are needed that support interoperability on multiple levels. The communication channel must be well defined, and the exchange of information should use common syntax and semantics. A common functionality is needed to support the grid services. Finally, support of well defined engineering workflows, system management and configuration procedures is also needed for aggregating and lowering the overall integration cost which in turn requires standardization.

The commercial aspects of VPPs have been studied [2, 3] as well as scheduling [4], control and dispatch [5, 6, 7]. Some implementation requirements are described in [5, 8]. What is missing in the scientific literature is proof that it is possible to build a VPP based completely on existing open standards. Such a proof first requires a systematic analysis of the functionality and need for information exchange of VPPs. Next, this functionality and need for information exchange should be compared with the standardized solution offered by existing state-of-the-art communication solutions. As such standards are still very much under development, it is likely that gaps will be found, requiring a gap analysis.

To propose a scientific methodology for implementation of VPP, a mapping of VPP services is provided to the services and information models of the international standards for power utility automation, IEC 61850 and IEC 61968/61970 Common Information Model (CIM). The mapping is provided in *a constructive manner* as follows: a set of selected grid services from the VPP has been identified and the corresponding IEC artifacts are suggested based on the analysis of functional requirements The VPP functionality has next been implemented in a Research, Development and Demonstration (RD&D) platform.

Section II and III of this paper gives a comparative study of how communication techniques proposed for VPPs fulfill the interoperability requirements of existing Smart Grid architectures. The gap analysis based on available standards is summarized in Section IV. Section V describes the VPP to which the proposed architecture is applied; the mapping is provided in a constructive manner in Section VI as well as results from the implementation of the proposed VPP in an RD&D platform.

The feasibility study of the Virtual Power Plant (VPP) was undertaken within a joint development project at the HVV (www.highvoltagevalley.se) titled "Smart Grid Energy Storage" and co-financed by the Swedish Governmental Agency for Innovation Systems.

The assessment of open communication standards for VPPs was part of the EIT InnoEnergy INSTINCT project.

II. Smart Grid Architectures for VPP

A VPP requires information from a large number of application domains (wind, hydro, solar PVs, storage, market operation, demand response schemes, etc). This section analyzes the requirements of a VPP using the Smart Grid Architecture Model (SGAM) [9], which has been developed by CEN, CENELEC and ETSI standardization bodies in response to the European Commission mandate M/490 [10]. This framework has been selected over the IntelliGrid Architecture from Electric Power Research Institute (EPRI) [11] and IEC reference architecture for power utility automation [12, 13] due to the SGAMs distinction of interoperability requirements on protocol, information, functional and business level.

The SGAM model divides the components of the power system into domains and zones, see Fig. 1. The DER system management spans the process, field, station and operation zones [14] and the distribution and customer premises domains. Interactions also exist to enterprise and market zones and, potentially, to the transmission domain.

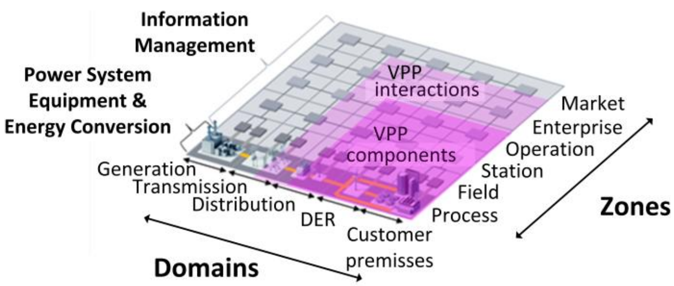

Fig. 1. SGAM Smart Grid domain, planes and hierarchical zones. Reproduced from [9] with participating VPP units and external interactions

The SGAM model further defines five layers of interoperability between components, communication protocols, information models, functions and, finally, between business objectives and processes. Using the five interoperability dimensions of the SGAM model, the requirements of Section V.B to V.D can be mapped to the layers of the SGAM model as shown in Fig. 2.

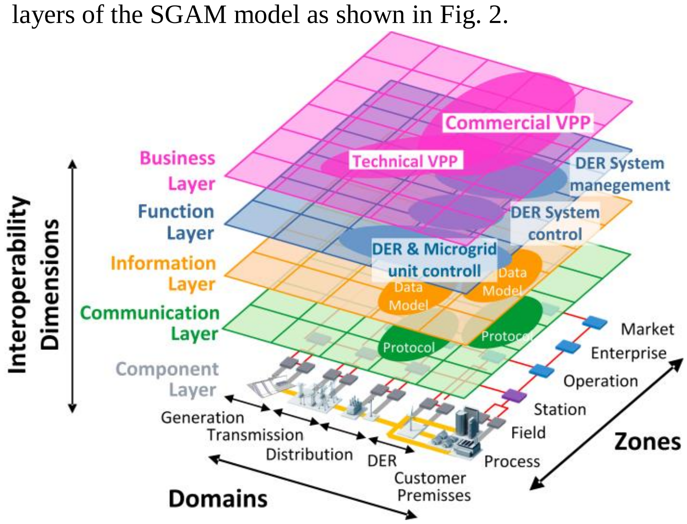

Fig. 2. Mapping of the Virtual Power Plant business, function, information and communication requirements to the SGAM Smart Grid model.

III. Comparison of Communication Solutions

Proposals in the literature for implementing VPPs also include the use of message-based middleware software [15], web services [16] as well as OPC [17]. The use of IEC 61850 for VPP has been proposed [18, 19] including field test in [20].

The use of Web services as protocol for IEC 61850 in order to achieve a Service Oriented Architecture (SOA) has also been proposed [17, 19, 21]. Table I compares the communication techniques proposed for VPPs with respect to the various interoperability dimensions in the SGAM model.

TABLE I. Comparison of communication solutions for VPP

	Interoperability on SGAM level			
Communication Solution	Com.	Info	Funct..	Busin.
Middleware software	Prop.	-	-	-
Web services	Std.	-	-	-
OPC-UA	Std.	-	-	-
61850	Std.	Std.	Std.	-
CIM	-	Std.	Std.	Std.

Prop. = proprietary solution, Std. = international standard

As seen in Table I the main difference between the communication solutions lies in the use of semantic information modeling and the extent to which the solution also can provide standardized functions and address business objectives and processes in a standardized way. To fulfill the full interoperability requirements described in Section II a solution today requires several standards.

It should be noted that the requirements on higher level of interoperability does not eliminate protocol solutions lacking semantic definitions. From a contextual point of view, several of the alternative proposals are better understood as alternative carriers of data on the communication dimension of the SGAM model. However, their use on the lower interoperability dimensions will eliminate the possibilities for seamless integration, requiring engineering effort in the absence of standardized data model, engineering processes and support for function and business layers of the SGAM model.

Indeed several assessments of Smart Grid standards have come to recognize the importance of the higher interoperability dimensions. The US National Institute of Standards and Technology Smart Grid Interoperability Panel initially indicated five "foundational" sets of standards, related to CIM, IEC 61850 standards [22], albeit the list has since been extended to some 75 standards [23]. In the IEC Smart Grid Standardization Roadmap [13] and reference architecture [12] IEC 61850 are used for the device to application communication while CIM is preferable for inter application information exchange. Referring to Fig. 2 the zones for IEC 61850 are from operation down to process level and for CIM from operation up to the market zone.

A. CIM

The Common Information Model (CIM) is standardized as IEC 61970 for application program interfaces of energy management systems within the transmission domain. CIM has been extended as IEC 61968 for distribution domain and as IEC 62325 energy market communications. At distribution level it is used for information exchange between applications for energy management, operation, and asset management. [24]. CIM defines classes, attributes and relationships using Unified Modeling (UML), which allows a stringent and consistent modeling [25]. The model also includes definition for asset tracking, schedules and customer billing [26]. European transmission system operators have decided to use CIM for exchanges of system operations and system studies [27]. The CIM modules are not completely harmonized with IEC 61850 and today require manual mapping of CIM equipment to IEC 61850 Logical Node instances and of CIM measurements to data attributes in IEC 61850 [20].

B. IEC 61850

IEC 61850 is an information model and communication architecture standard developed to allow interoperability within power utility automation systems [28]. Originally intended for use within substations at transmission level, it has been extended to cover new domains such as wind (IEC 61400-25), hydro power (IEC 61850-7-410) and several types of DER (IEC 61850-7-420) as well as new application areas like inter-substation and substation to control center applications [29]. The standard is becoming the most common substations communication solution at higher voltage levels in many countries. At the end of 2013 some 90 manufacturers in more than 20 countries had certified devices for the standard. Today solutions exist to run IEC 61850 software protocol stacks also on low cost microprocessors.

The application view and object-oriented structure of IEC 61850 is described in [30, 31]. In IEC 61850 a Logical Node is a virtual representation of the communication interface for a primary apparatus, protection and control function or measurement value. Logical Nodes are grouped into Logical Devices implemented in Intelligent Electronic Devices (IEDs). A power utility automation function is realized by a set of collaborating Logical Nodes distributed over IEDs [32].

In IEC 61850 Logical Nodes, data objects can contain multiple attributes including quality, time stamp and even, if required, currency information. The standard today allows the grouping of Logical Nodes into functions and sub functions in a topology related data model. The same information can be grouped into components and sub components in a parallel product view of the IEDs. A gateway device may also hold a representation of non-IEC 61850 devices to which it communicates. This allows flexible modeling where information from simple and diverse IEDs of the participating DER can be efficiently structured in a hierarchical model within the VPP.

The model and system configuration can be specified on a functional level allowing free allocation of the functionality to various Intelligent Electronic Devices (IEDs) used for protection, control and monitoring. Information from the IEDs can be sent to gateways or directly to SCADA and EMS systems. This makes the standard very appropriate for modeling of complex distributed systems.

The protocols used to send IEC 61850 information are generally not defined in the standard itself, only the mapping to a limited number of protocols standardized elsewhere is included in the standard.

As IEC 61850 covers data models for a broad range of VPP components they can interact through a coherent information model using standardized semantic, syntax and service-oriented communication interface. Extensions are on-going to new domains like electrical storage and to make IEC 61850 applicable for new application areas and lower voltage levels. Some demonstration projects are now going as far as proposing the use of IEC 61850 for all the communication concerning the electrical domain [33].

IV. Required Adaptations of IEC 61850 for VPPs

IEC 61850 enables well-defined system interfaces between different DER units using standardized interfaces; however, functionality for scheduling as well as management and aggregation of DER required by a VPP is lacking. Scheduling does exist in the wind power variant of IEC 61850 (IEC 61400-25) and is a planned extension. An upcoming part (IEC 61850-90-15) regarding "Hierarchical DER System" intends to fill the gap required for aggregation and DER management and will also allow "mapping of DER-type specific information into a generic DER-type independent data module" making aggregation more efficient [14].

According to IEC 61850-90-15 the VPP is intermediary for requests from clients seeking information from the DER units on process level. Several interfaces exist between the VPP controller, the DER units and market actors as given in Fig. 3. IEC 61850-90-15 distinguishes between commercial (participation on wholesale markets) and technical VPP (support for the local grid). Commercial VPP is mainly part of the enterprise and market zones of the SGAM model and thus associated to the IEC 61968 CIM (see Fig. 1). The technical VPP covers communication between field, substation and operation zones associated with IEC 61850.

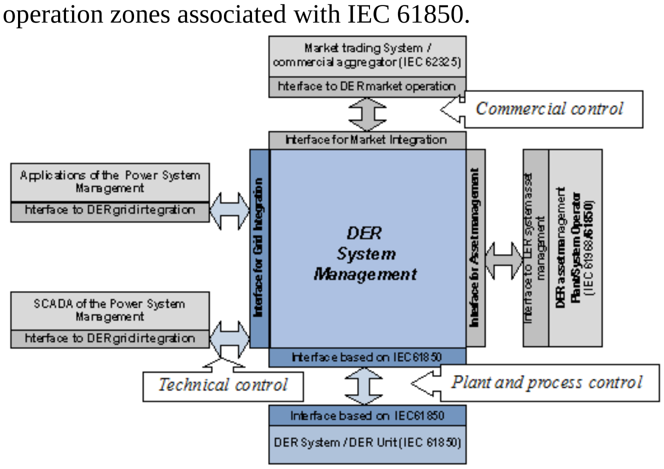

Fig. 3. Interfaces of the VPP to grid operator and market, according to IEC technical committee 57, working group 17

IEC 61850-90-15 will describe a number of services required by a VPP. This will include administration functions that allow the VPP to maintain a registry of the DER units. Lacking in the IEC 61850 standard today are also dynamic system management services to allow a DER to register to a client specified with only its IP-address. The client can then query the characteristics and properties of a DER and subscribe to specific services controlled by the VPP. In a longer perspective standardized services such as those described for PV and other DER inverters in IEC 61850-90-7 could be subscribed to automatically. Such functions include freq-watt, volt-watt control of active power and fixed power factor, fixed VAr, Volt-VAr and Watt-power factor control. Using such advanced DER characteristics, the VPP would need only to optimize the settings of the various DER, rather than continuously adjusting set points.

Based on its database the IEC 61850 VPP could, with these additions, respond to requests from a Distribution Management System (or a market trading system) providing characteristics, properties and a response with available capacity. The database is then updated with real value parameters and real time estimates of available capacities.

V. Description of the VPP

The VPP implementation, used as a reference in this paper, is based on existing and modeled DER in a real 50 kV grid. The VPP includes an existing 34 MW wind park and 6 MW run-off hydro-power plant with a reservoir that can store the equivalent of 111 MWh production. A 3 MW PV installation and 8 MW / 32 MWh battery energy storage system (BESS) are based on data from smaller units in a nearby RD&D. The wind park and the PV installation are not controllable; their production is determined by the availability of sun and wind. Variations from these two sources can be compensated by the hydro-power plant and the battery storage.

A. Simulation Results

The simulation results presented in Table II show that the VPP under study is able to make a substantial contribution to the operation of the subtransmission grid next to its contributions to the national market and system operation. The results are based on simulations using three-years of hourly consumption and production data found in [34].

The VPP's applications for grid and system support listed in Table II were selected based on a literature study presented in [34] and discussions with the local Distribution System Operator (DSO). Such ancillary services go beyond the mere market value of the produced energy. For example, many DER units have power electronic converters that are able to provide capacitive or inductive reactive power to help maintain voltage levels. Often these units are set to keep reactive power near zero at the DER connection point. The potential to coordinate these reactive power capabilities to optimize the overall efficiency of the grid(s) in which the DER units are located are then not fully utilized.

TABLE II. Selected Grid Services from the VPP

Grid service	***Found Gain***
Balance responsible party (B): Compensate for prediction error from wind and solar. The hydro reservoir is used with battery storage to allow the VPP to act as a balance responsible party and meet the forecasted production of the day-ahead spot market of the wind and solar units. In this way the next day stated capacity of the DER units can be met. The limitations set by the 50 kV grid on market transactions are specifically part of the assessment.	230 *kEUR/yr*
Peak monthly power reduction (P): Reduce subscribed power to regional 130 kV grid. This application reduces thermal overload, increasing the grids hosting capacity.	50 *kEUR/yr*
Minimize grid losses (L): By smoothing peaks in the power flow the losses in the subtransmission grid are reduced.	Not measureable
Control reactive power flow (R): Lower the reactive power flow through the 130/50 kV transformers by coordinating DER reactive power control possibilities.	6 kEUR/*yr*

Studies of similar applications of VPP for reactive power compensation are described in [35, 36], for improved system efficiency in [1] and to optimize power flow and minimize the peak load in [5]. A commercial value in kEUR of the estimated annual gain of each grid service is included in Table II, based on [34]. For balancing (B) the gain is non-purchased balance power, for peak reduction (P) lowered tariff to regional grid, for loss reduction (L) the costs to cover losses in the local grid. For balancing (B) and the reactive power compensation (R), the value is also in the increased hosting capacity (ability of the grid to host more DER see [37]).

The different applications of the VPP use the storage resources with different priority. The peak reduction application (P) uses primarily the hydro reservoir. The applications B and L use first the battery storage, turning to the hydro storage only in extreme circumstances when other applications are down prioritized. The prioritization of the services is internal to the VPP controller and does not affect the required information exchange.

B. Functional Requirements

The grid services in Table II require the following functionality group according to [14]:

- DER System Management: Connect a DER to the VPP controller, reading service capabilities of the DER and updating the VPP list of resources and capabilities according to grid topology.

- DER System Control: Services for data acquisition, monitoring of an aggregation of DER as well as split and distribution of control requests to the various DER.

- DER or microgrid unit control: supervisory control and data acquisition of the units participating in the VPP. The balancing (B) and peak power (P) applications require the VPP to calculate individual set points for active power. The grid loss (L) and reactive power compensation (R) require reactive power set points to be calculated and sent to individual VPP units.

C. Information Requirements

The required information to perform the applications described in Table II consists of both commercial data from market traders, real-time information from the included DER and measurement of power flow and voltages in the distribution grid. Table IV summarizes the required information to perform the applications in Table II. Some of the information is optional (indicated with 'Op') to improve performance, but not essential for the basic application.

The VPP needs to communicate both with the DSOs SCADA system and equipment in the grid in order to gather information. There is also need for information exchange between the VPP and market actors. Based on the Cell Controller architecture [38, 39], the design uses semi autonomous agents in the form of Intelligent Electronic Devices (IEDs) and VPP controllers. Each VPP controller receives commands and set points from overlying layers but otherwise acts autonomously, considering its own operational limitation, as shown in Fig. 4.

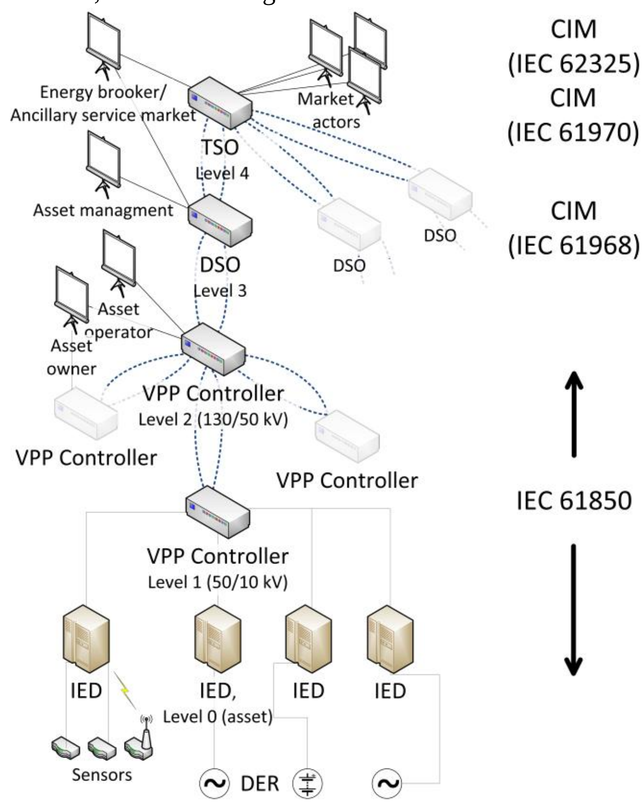

Fig. 4. VPP architecture using a hierarchical structure. Interactions with asset owner, operator system operators and market actors are shown (left) as well as proposed information models for the data exchange (right).

D. Communication Requirements

For the studied applications data on the grid voltage, power flow and DER production are sufficient on a 1-minute scale. To acts as balancing party and compensate for prediction errors in day ahead and intraday bids, 15 minute update intervals are expected. To compensate for deviations within the interval, minute updates for production and storage set points are anticipated. These moderate requirements are supported by trial implementation of application (R), with 5 minutes update intervals [35]. However, applications like control of reactive power to compensate short-term voltage variations require update intervals less than one minute.

With a large number of DER in a VPP the failure of individual DER to participate in a request is not crucial, so availability requirements are moderate. The proposed VPP is intended for a subtransmission grid where all substations are accessible over Wide Area Network (WAN) at speeds of 100 Mbit/s. In Sweden it is not unusual for 10 kV substations to have WAN access making bandwidth efficiency of used protocols less important than with e.g. power line carrier techniques. The bandwidth efficiency is still a concern for retrieving sensor data over wireless links or from energy meter outside the substation [40, 41], although Wireless LAN with IEC 61850 for distributed automation is viable [42].

A request from overlying VPP controller will result in the calls to all participating DER. If the number of DER participating in the VPP is large the simultaneous response of these units will lead to peaks in the used communication bandwidth. If this is a concern similar functionality as defined in IEC 61850-90-7 [43] could be implemented to randomize time of response within a provided time window.

E. Communication system security requirements

As the VPP acts within a utility WAN the IT security is enforced only at the external gateways to the WAN. For commercial operation access to individual DER at owner premises is a concern. Methods to ensure data integrity and distinguish rough commands from those of VPP controller must then be ensured. This could be done through authentication and confidentiality services based on encryption and key management under development as IEC 62351 standard, or through other means [44, 45, 46].

VI. Implementation

In order to verify the maturity and performance of the proposed architecture the VPP functionality has been implemented within a Research, Development and Demonstration (RD&D) platform. The implementation is in some case made according to committee drafts of standards still pending final approval within the IEC.

The installation includes real-time communication from the MV distribution grid as well as status information from a nearby hydro power plant and wind park. The RD&D enables development and verification of control algorithms for VPPs in order to gain experience in their practical deployment and operation. The RD&D facilities include 30 kW solar PV and 30 kW / 20 kWh lithium-ion battery storage. The DER units are monitored and controlled from an IEC 61850 capable SCADA that acts as a VPP aggregator.

A. Mapping to IEC 61850 Data Models and Services

Table IV presents proposals of appropriate IEC 61850 Logical Nodes, data and services to be used in the implementation of the VPP applications described in Section V. For data acquisition and monitoring between the VPP controller and the DER units generic measurements (MMXU Logical Node from IEC 61750-7-4) are mostly used. This approach was required as most commercially available IEC 61850 DER implementations do not yet use the IEC 61850-7-420 Logical Nodes for DER system rated characteristics, operational characteristics, supervisory control, set point allocation and operation mode. The IEC 61850 modeling concepts are also significantly different and more extensive than other solutions. Specific functionality, services and points of measurement are mandated that required more than a direct one to one mapping of existing Modbus interfaces in the DER.

The IEC 61850 modeling of the BESS was created by the authors, providing full freedom to implement the IEC 61850-7-420 standard. Due to ongoing extensions and revisions of the standard the battery models were ambiguous at the time of writing, in some cases providing up to four alternative mappings for the same internal BESS variable, according to IEC 61850 parts under various stages of drafting and approval. To align the vendor's propriety battery management system and the IEC 61850 implementation the choice fell on using first standard edition's ZBAT Logical Node and introducing an extension to it for the percent battery state of charge.

In total 28 different IEC 61850 servers are present in the RD&D, including protection relays, communication network equipment, power quality meters, transformer supervision and battery storage. See Fig. 5 for extracts of their modeling.

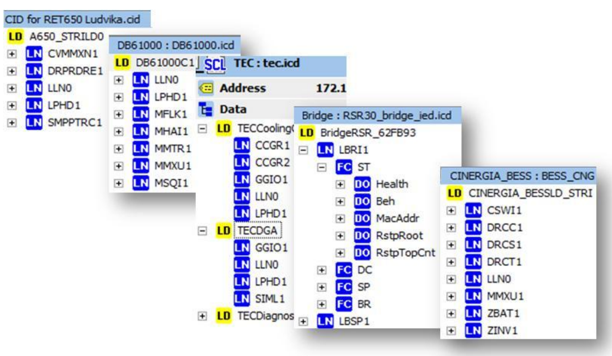

Fig. 5. IEC 61850 data model of inverter controller of the protection relay, power quality meter, transformer supervision, bridge and battery storage

IEC 61850 supports four different data access methods. The principle characteristics of these are given in Table III. The VPP uses unbuffered reporting for measurement and buffered reporting service for status values. Due to limitation in some IEDs the polling service is used instead of reporting for retrieving status values. The IEC 61850 control is according to IEC 61850-7-2. Further information on the control is given in the description of each application implementation (Section D and E).

The services defined in IEC 61850-7-4 for statistical and historical data allow the VPP controller to keep track of power flows and limits. These services did not exist in the IEC 61850 servers, instead the functionality was implemented in the SCADA system.

TABLE III. COMPARISON OF THE DATA ACCESS METHODS IN IEC 61850

Retrieval method	Time-critical	Can lose changes	Multiple clients	Last data stored by	Typical client
Polling (GetDataValues)	NO	YES	YES	–	Browser
Unbuffered Reporting	YES	YES	NO	–	Real-time GUI
Buffered Reporting	YES	NO	NO	Server	Data concentrator
Log (used for SOE logging)	NO	NO	YES	Client	Engineering stations
GOOSE	YES	YES	YES	–	IED (peer-to-peer)

B. Configuration

The participating DER units must be assigned an IP-address within the VPPs subnet. The VPP can then configure the data retrieval and commands to the DER. Configuration can be done either off-line with the Substation Configuration Language (SCL) description (as defined in IEC 61850-6) or online through browsing the DER content with MMS/ISO9506 protocol (as mapped in IEC 61850-8-1), see Fig. 6.

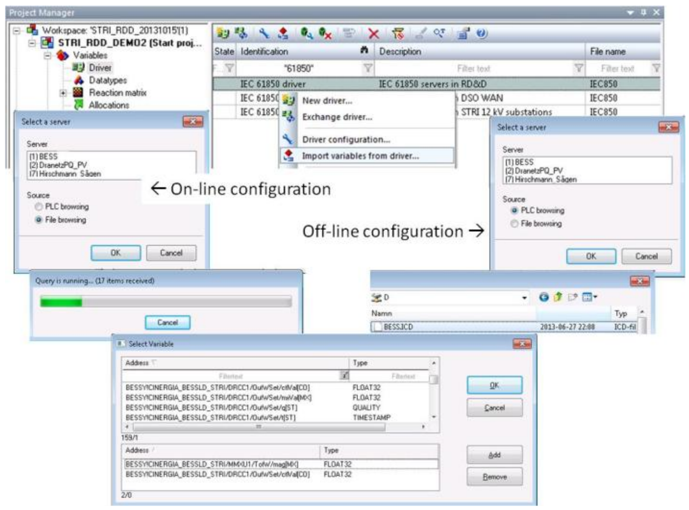

Fig. 6. Configuration of the VPP controller can be done off-line using IEC 61850 SCL files (left) or on-line with MMS/ISO9506 protocol (right). In both cases the result is a list of available IEC 61850 variables (bottom).

When the required data is available in reports, the reports are subscribed to, otherwise the data is polled. The option to poll data minimizes the requirements on pre-configuration in the DER units for participation in the VPP. This reduces complexity, engineering time and lowers the integration cost.

C. Communication

IEC 61850 as a communication solution has good performance in terms of scalability, efficiency, reliability and availability compared with other SCADA protocols like IEC 60870-5-104 [47]. The use of IEC 61850 is not designed to minimize bandwidth and more information such as object labels, types, extensive quality information and timestamps are sent compared to other protocols. The MMS/ISO 9506 used for reporting typically consumes 3 to 10 times more bandwidth than other alternatives [47]. However, as seen in Section V.B, this is not a major concern for the proposed VPP since broadband WAN access is available to DER units.

Bandwidth use is still moderate for the implemented VPP. From the 12 kV relays, data is retrieved with reporting service (see Table III) requiring 0.25-1 kBytes/s per IED. Some data is also available using the peer-to-peer GOOSE service defined in IEC 61850-8-1. This requires 0,01 to 0,3 kBytes/s for messages containing 2 to 10 data attributes repeated at intervals of either 750 ms or 10 s, depending on data usage.

Through a dedicated Virtual LAN (VLAN) within the DSO WAN the facilities have access to equipment in the distribution grid. An IEC 61850 capable power quality metering system is installed in a dozen locations within this distribution grid allowing measurements from locations in the grid to be used by the VPP. The 50/10 kV substation of the wind park is 15 km away and passing either 14 or 15 switches (hops) depending on the switching tree. Measurements show delays of less than 1 ms on ping. While the DSO power quality monitoring system uses proprietary TCP/IP communication, the VPP can in parallel retrieve data via IEC 61850 polling routed on separate VLAN. The per second polling of 39 IEC 61850 data attributes results in on average 6 kBytes/s, doubling during shorter periods as shown in Fig. 7.

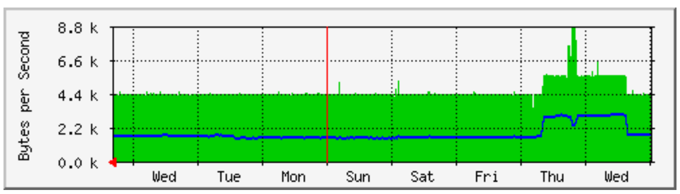

Fig. 7. IEC 61850 data traffic for polling of one IEC 61850 server within the DSO WAN. Blue/line is poll requests over MMS (ISO 9506) and green/bar is the corresponding traffic load from data response. The product does not support the reporting service.

To find the bandwidth use for a VPP with the applications in Section D and E an embedded communication simulator could be integrated with the power system simulation tool as described in [48], or co-simulation performed [49].

D. Balancing and peak reduction

For applications B and P of Table II the VPP monitors the battery storage and controls active power using the Logical Nodes for DER supervisory control, controller status and controller characteristics (DRCC, DRCS, DRCT) defined in IEC 61850-7-420. The active power is set with DRCC.OutWSet.ctlVal. To demonstrate the ability to control active power the response from PV installation and Li-Ion battery storage is increased to represent the larger storage and PV in the studies when simulating the VPP effect on the grid. The active power set points of the BESS is determined through a Proportional Integral Derivative (PID) control loop, implemented in the SCADA VPP controller, see Fig. 8.

The hydropower installation is not controllable with IEC 61850 at this stage. If its controller was retrofitted with an IED that implemented IEC 61850-7-410, the active power output would be controlled by the automatic power regulator Logical Device. The active power set point control function for active power (standardized prefix W_+FSPT.SptVal) is then activated by the hydro governor (HGOV). The wind park, when modeled according to IEC 61400-25, would allow control of active power output through the Logical Node for active power control (WAPC). First the active power control function is activated with data object PlWAct followed by setting reference value for the wind power plant active power output with WAPC.SptPlW. The inverters of the PV could be commanded to participate in the reactive power production/consumption via a modified power factor. (For a single wind turbine the Logical Node WTUR would be used instead.) Following the IEC 61850-90-7 technical report “Object models for power converters in distributed energy resources (DER) systems” the VPP could interact with the PV converters using immediate control functions to curtail production. This would be done by invoking function INV2 “adjust maximum generation level down”.

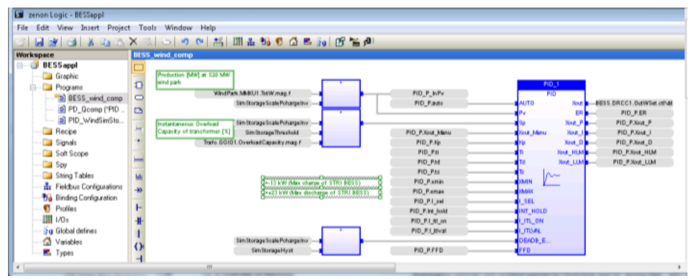

Fig. 8. Control of BESS active power using the SCADAs built-in soft PLC (Programmable Logic Controller). The control loop inputs are wind park production, transformer loading capacity. A single Proportional Integral Derivative (PID) function block determines the BESS active power set point.

E. Loss minimization and reactive power

For applications L and R in Table II the reactive power set points of the BESS are controlled via DRCC.OutVarSet.ctlVal. The BESS converter is based on two Voltage Source Converters (VSC) of 50 kVA. The converter switching technology is based on Insulated-gate bipolar transistors (IGBTs) ensuring the bidirectional capabilities needed for freely setting reactive power independent of the active power within the operational range (-13 kW to + 23 kW and ±30 kVAr). The SCADA receives measurement of the reactive power on the HV side of a 12 kV transformer from the protection and control IED. The BESS reactive power set points is determined by a single PID loop. Fig. 9 shows the application in the SCADA VPP controller.

For the hydro power plant to perform the simulated reactive power contribution in [34], a separate instance of the set-point control function Logical Node (including recommended prefix: VAr_FSPT.SptVal) would be used after control mode is activated with control mode selection VAr_ACTM. For wind the reactive power control (WRPC) is used. For wind park reactive power control the function is first activated with WAPC.PlVArAct and reference value of wind power plant reactive power output then set with WRPC.SptPlVAr.

For PV control the VPP could, following IEC 61850-90-7, use immediate control functions for power converters (INV3) to adjust power factor or use Volt-VAr management mode

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(VV13) to send near real-time updates of fixed VAr settings for power converters. However, due to the frequent (tens of seconds) variation in solar power caused by passing clouds it would probably be more efficient to use autonomous Volt-VAr management modes. The PV would function according to a defined Volt-VAr curve requested to switching from Volt-VAr mode (VV11) without active power reduction to mode (VV12) with maximum VAr support in contingency or stressed grid operation states. A further possibility is the GOOSE interface that exists for the converter according to Italian directive AEEG 84/2012 [50]. At present this national mandate stipulates to support disconnection and stay on grid frequency limits but could potentially be expanded. The advantage of GOOSE is that it is a multicast message (i.e. layer 2 protocol and not IP-based) and can be configured to transverse different IP-networks.

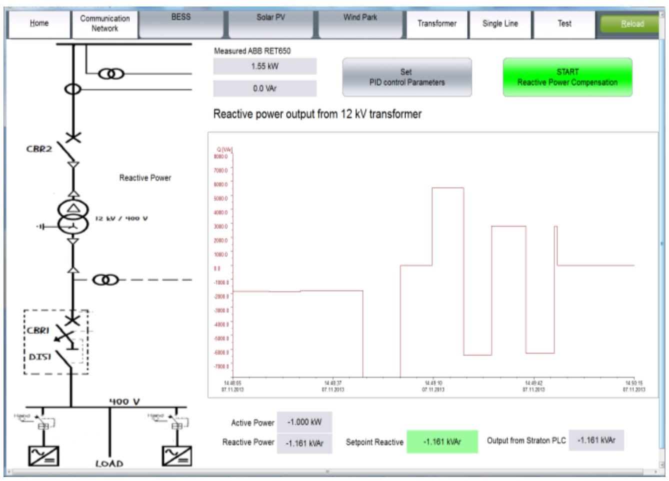

Fig. 9. SCADA IEC 61850 control of BESS reactive power where the measurements from an IED on the HV side of a 0.4/12 kV transformer is used in a control loop, allowing the BESS and PV sub-grid to have unity power factor with the connected 12 kV grid.

VII. Future Work

A. *CIM for information exchange with overlying systems*

To implement and verify the entire architecture described in Fig. 4 the VPP controller needs to translate received IEC 61850 information to CIM to for interaction with overlying systems. The feasibility of including in a substation the middleware to semi-automatically translate IEC 61850 data to CIM is shown in [20, 51]. This would allow CIM to be used for communication between VPP application and utilities and market traders. In this way the topological origin and information content of the IEC 61850 data is preserved throughout all systems and applications using the data.

B. *Real-time estimation of transfer capacity*

Application P of Table II uses static limits to the allowed power transfer. With real-time information on the transfer capacity of the grid such static limits could be replaced with real-time assessments depending on the actual state of the grid. The RD&D platform includes a transformer supervision system mounted on the 12 kV transformers that enables real-time reading of the transformer loading capacity, see Fig. 10. In this way DER could be allowed to send in more energy than permitted by static design limits. The loading capacity is calculated using temperature sensors and current and voltage measurements from the protection relay on the 12 kV and the BESS on the 0.4 kV side. During an overload the transformer supervision can also take over control of the BESS from the VPP controller and charge the BESS to mitigate the overload.

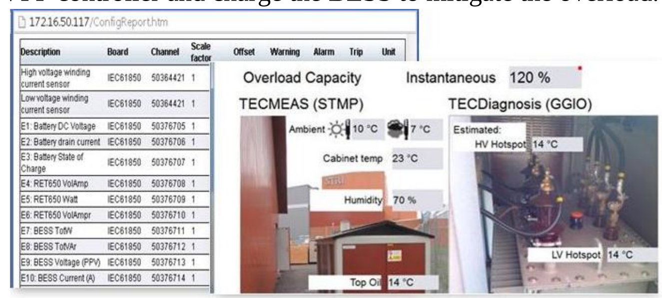

Fig. 10. SCADA IEC 61850 control of BESS reactive power where the measurements from an IED on the HV side of a 0.4/12 kV transformer is used in a control loop, allowing the BESS and PV sub-grid to have unity power factor with the connected 12 kV grid.

If also the real-time rating is calculated for lines in the grid, the hosting capacity for new production can be increased with 50% to 100% depending on the production mix [52]. This could be by implementing IEC 61850 in the wireless temperature sensor network already present in the RD&D. It could also be done with tension cells that give an indication of the average temperature over a greater line segment [53].

VIII. Discussion

With the introduction of low cost gateways and integration software the cost of implementing IEC 61850 has been reduced considerably. Several commercial SCADA systems support IEC 61850 and the standard is being developed further to cover substation to control center communication as well. Other work has shown how to disperse part of the intelligence from control center (CC) to other levels of the distribution grid using IEC 61850 compatible SCADA systems [47]. IEC 61850 therefore promises to provide a cost effective, flexible, open and extendable solution to a VPP providing grid services. This VPP could use bi-directional IEC 61850 communication to MV and LV substation, DER units as well as to demand-response providers. In the implemented IEC 61850 based architecture each server is able to connect to multiple clients. This mitigates today's restrictions where grid related data is often only available to the DSO, requiring the VPP controller to be placed in their WAN and limiting the ability for market actors other than the DSO to operate a VPP for grid services.

In this study the number of DER units to be integrated in the VPP was limited and only a small amount of information was required by the VPP controller. With wider vendor support for domain specific IEC 61850 extensions for wind, hydro and solar PV a flexible VPP controller would be created where additional information available from DER can

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be browsed and included in control algorithm as required to improve functionality and performance.

As described in Section IV, IEC 61850 could in the future be extended with system management functionality that allows the DER, provided only with the VPP controllers IP-address, to directly register itself with a VPP controller. The VPP controller would then be able to read out the services and capabilities of the DER and automatically include it in the VPP. This would allow regulators to mandate specific functionalities in future DER in a similar manner to the EU directives on eco-design [54]. The DSO could then provide the communication interface to customers applying for permission to connect PV or an Electric Vehicle (EV). The end users would be obliged to enter the IP-address in the DER user interface. The rest of the VPP configuration would be automatic. As the functionality and interface become standard, this approach would add only marginal to the DER cost but would enable wide scale use of grid services. Experience from the 1980’s with remote control of hot water boilers in Sweden and Switzerland show that customers worry little about such interactions if the basic service of an electrical device is not affected [55]. As long as there is no significant life-time shortening or increase in losses, it is thus plausible that end-users would care little if their PV converter or EV chargers are providing grid services like the grid reactive power support described in this paper.

IX. Conclusion

To form a VPP, interoperability is required on communication, information, function, and business objective dimension. In order to achieve an efficient, flexible and scalable solution, the integration of the VPP functionality must be seamless maintaining the information content (semantics) throughout the information flow from process to operation and market actors, passing on the way several controllers and applications. This limits the choice of communication solutions available for a generic VPP. It is shown that an architecture based on CIM and IEC 61850 can fulfill the VPP requirements.

The IEC 61850 standard includes domain specific information models for most DER types. Proposals are given for system management extensions of the IEC 61850 standard to enhance the interaction between VPP and the distributed energy resources. With such extensions the IEC standard can contribute to seamless integration of the DER data to a VPP and ease integration to market applications when the VPP enables conversion between IEC 61850 and CIM. Extensions of the standard are required to support scheduling, management and aggregation of DER for a VPP.

In order to prove the viability of the proposed IEC 61850 based VPP the implementation of the communication and control architecture in a SCADA is shown.

TABLE IV Required Information and Suggested Mapping to IEC 61850 for the Applications of Table I

Information	**Table I Appl.**				**Description**	**Data source**	**IEC 61850**	
	B	P	L	R			***Logical Nodes***	***series part***
Predicted Production	X	X	X		Bid on the day-ahead spot market. (24 bids placed 12 a.m. for next day.)	Forecasting tool used by Electricity retailers[a]	*Use of IEC 61850 not anticipated, although schedules from upcoming IEC61850-90-10, using FSCH, FSCC Logical Nodes could be used.*	
Intraday correction of predicted Production	X				Bid on intraday market. (One bid per hour, latest an hour before period starts.)	Forecasting tool used by Electricity retailers[a]		
Battery storage State-of-Charge	X	X	X		Amount of Stored energy in BESS.	Battery storage controller	DBMS	To be defined in upcoming 90-9
Hydro reservoir water level	X	X	X		Amount of Stored energy in hydro reservoir.	Hydro plant producer or controller	HLVL.LevM	7-410
Real-time production of DER	X	X	X	X	To determine accumulated production within present hour. Also used together with latest bid to estimate production for present hour.	SCADA or DER controllers	MMXU.TotW MMXU.TotVAr	7-4
Latest Regulating volume for price area	Opt				To predict if over or under production (compared to prediction) will result in economic cost.	Electricity market broker	*Use of IEC 61850 is not anticipated*	
Weather data used for retailers prediction	Op				Wind speed, rainfall, irradiation etc on which production prediction where based. Used to estimate if bids during present hour are accurate.	Electricity retailers	*Use of IEC 61850 is not anticipated*	
Real-time weather data	Op				Actual weather data within hour to enable estimation of prediction error for present hour.	Measurements at DER or metrological bureau	MMET. HorWdSpd, DctInsol, CloudCvr	7-4, IEC 61400-25
Long term production forecast	Op				Optimize BESS State of Charge and hydro reservoir level (beyond 12-36 h period forecasted in spot bid)	Electricity retailers or DSO/TSO forecasts	*Use of IEC 61850 not anticipated, although schedules from 90-10 possible*	
Historical levels of power flow		X	X		Determine if VPP shall attempt to lower peak flows to reduce tariff or losses. Based on historical hourly power flows or logged data.	VPP controllers log of real time production	VPP historical statistical information model of MMXU.TotW	7-2
Highest power flow during current month		X			Block power flow reduction if monthly maximum will not be exceeded.	VPP controllers log of real time production	VPP statistical information model of MMXU.TotW	7-4 (and 7-1)
Power flow in grid location(s)		X	X		Determine if peak power flow and high losses are occurring.	SCADA or IED meas-urement within grid	MMXU.TotW	7-4
Real-time voltage at DER			Op		Calculate losses more accurately when voltage varies considerably at DER.	SCADA, DER cont-roller or IED near DER	MMXU.PhV	7-4
Reactive power in selected location(s)				X	Reactive power flow at a point(s) in the grid for which reactive power exchange is to be optimized.	SCADA or IED meas-urement within grid	MMXU.TotVAr	7-4
Real-time voltage in grid				Op	Calculate ΔQ required from DER to hold voltages in selected point(s) of the grid within limits.	SCADA, IED in grid or smart metering system	MMXU.PhV	7-4

[a] In contrast to other sources like IEC Smart Grid Standardization Roadmap [16] the VPP is not by itself expected to make more than one hour forecasts. The energy traders are expected to use existing software for prognosis and the results thereof fed into the VPP controller.

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