Siemens Smart Grid Innovation Contest

Integrated Architecture and Programming Model for Distribution and Microgrid Automation

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1 Abstract

This idea proposes methodology known as *integrated architecture* for the design and deployment of distribution automation computing and communication infrastructure. By giving parallels to the ongoing efforts with the AUTOSAR standard in the automotive industry, we argue that in order to keep increasing software development costs low, the power systems industry has to go beyond current standards such as IEC 61850. We identify a technical problem with these standards and suggest a solution based on a programming model with clearly defined semantics. We discuss business models and benefits of the integrated architecture approach for all main stakeholders. Throughout the whitepaper we present data and references to the U.S. power market.

Contents

2 Idea Description

2.1 Motivation and Market Drivers

The evolution of the Smart Grid parallels what was previously seen in the automotive industry, where a significant milestone was the transition from a carburetor to an engine control unit. Once that change was made, other processing units were being added to the point where nowadays there are vehicles with more than a hundred units. Similarly, the transformation of mechanical to digital meters on the power grid is presently being followed by control innovations such as reclosers, sectionalizers and substation automation.

According to [7] only about 10% of utility operated substations in North America have been fully automated and integrated by the year end 2010. The North American spending for distribution automation will increase from the current $500 million to $10 billion in 2014 and the world investments are predicted to total $46 billion over the next five years [28]. As stated in its recent deployment plan [8], the northern California utility Pacific Gas & Electric plans to spend until 2020 up to $1.25 billion on all its smart grid projects. A fairly large portion, $850 million, will be for distribution and substation automation, wide-area management systems and other system upgrades.

The newly *added functionality* increases system complexity and introduces new sources of uncertainty. Utilities and equipment suppliers are challenged to improve system *reliability* and restoration potential. For instance, in its recent project Sacramento Municipal Utility District put forward 25% reduction in SAIDI reliability indicator [10]. In addition, as the grid evolves, hardware components will be upgraded as warranted, based on load growth and criticality to customers. Software *updates* will also be needed to maintain operation or to adjust algorithms without infrastructure improvements.

Microgrids are being proposed to achieve specific community-established goals, such as carbon emission reduction, diversification and integration of renewable energy sources, as well as local power reliability. Analysts estimate 2011 world microgrid revenues at $200 million, with potential for the market to grow up to $3 billion by 2016 [29]. As envisioned in [16] microgrids will provide communities the control over their own energy consumption, rather than having it imposed upon them by a sole supplier. Thus, the consumers will be able to choose the quantity and quality of power that meets their needs. To achieve the higher energy efficiency and reliability potential of the microgrid concept, the communities will have to address the challenges of *component integration* and distributed nature of microgrid generation and storage.

The data from the automotive industry including [15], points that already by 2010, 40% of the costs of a vehicle is driven by electronics and software. About 60% of all development costs for a car electronic control unit is related to software only. In addition, while the number of processors is expected to average in the range of 60-70, the growth rate of software functions is 300%. Finally, around 90% of innovation is electronics-related, whereof 80% in the area of software. This increase of software use in vehicles is explained by several market requirements, including consumer personalization, car maker brand differentiation, safe-driving legislation, and connectivity to external devices and services. The similar data for power industry is hard to find, but we believe that most of these software-enabled functions will find their place in the smart grid ecosystem and some of them in the distribution and microgrid automation.

The requirements mentioned above, i.e., functional complexity, reliability, extensibility and integration, call for advanced design methodologies for the underlying communication and computation architecture. Several system-of-systems architecture patterns have been suggested for the overall grid IT architecture. These are mostly based on widely adopted standards, common services and

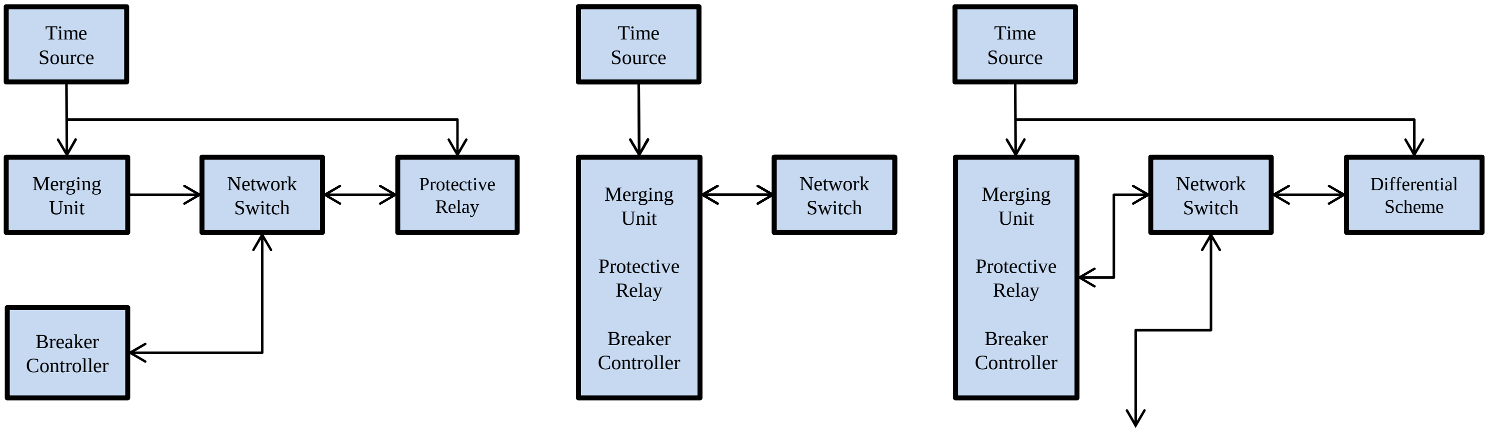


Figure 1: [L] Substation protection process. [C] Protection functions mapped on a single physical device. [R] Differential protection process.

loosely coupled systems [18]. In this idea we focus on low-level software layers of the architecture. We propose principles of the integrated architecture together with a suitable programming model for the design and deployment of microgrid and distribution automation.

2.2 Technical Goals

2.2.1 IEC 61850

Consider substation communications standard IEC 61850 [21] that is increasingly being used by utilities [7]. The standard prescribes how power system devices should organize data and specifies principles of data transmission protocols. Two different communication layers are defined, the process bus and the station bus. The process bus carries input and output signals among sensors (e.g. transformers), control devices and actuators (e.g. breakers) that are all located within a substation. The station bus represents a slower local-area network communication between the control devices, potentially located in different substations. The process bus concept proposes digitizing transformer outputs directly at the sources and communicating the data to the substation protection and control devices. Among the benefits of this technology are reduction of copper cable costs and elimination of some safety related problems, e.g. open current circuit condition [35].

However, the straightforward implementation of a process bus solution requires the introduction of multiple computing components where previously only a single multifunction relay was used. As shown in Fig. 1[L], such an implementation could consist of the following hardware components at each protection point: sensor merging unit, relay, breaker controller, network switch, and time (synchronization) source. As explained in [31], this solution suffers from a decrease in reliability with each introduced dedicated component. A better approach would be to identify groups of interdependent functions and, if physically possible, map each group on a separate hardware component (Fig. 1[C]).

To address these issues, the standard section IEC 61850-5 [6] first introduces notions of *physical devices*, *logical nodes* and *logical connections*. All system functions are decomposed into logical nodes that may reside in one or more physical devices. The logical nodes are linked by logical connections, which are also eventually mapped to physical network connections. The standard further defines about 100 distinct nodes in groups such as protection, control and security. Some applications such as differential protection schemes require separate physical devices (Fig. 1[R]), but in many cases multiple logical nodes can be mapped into a single physical device.

Data object models for microgrids and distributed energy resources are addressed in the section IEC 61850-7-420 of the same standard [5, 24]. A typical microgrid architecture is presented in [17] and consists of master and slave controllers. The master controller coordinates the set points for the individual generation, storage and load microgrid devices and provides the interface to the external electricity supply grid. For instance, as described on a setup in [30], active power control function is decomposed into a set of logical nodes distributed over controllers including nodes such as inverter, rectifier, switch controller, DC measurements, AC measurements and circuit breaker. In another solution, the Consortium for Electric Reliability Technology Solutions proposed a peer-to-peer concept for microgrids [20]. In a peer-to-peer solution there are no master and slave controllers or a central storage unit, and the microgrid can operate with a loss of a single component. However, function partitioning and integration issues occur in any microgrid distributed deployment.

2.2.2 Integrated Architecture

The integrated architecture has been introduced in avionics [36, 27] as Integrated Modular Avionics and has recently made inroads in other sectors such as automotive. As opposed to the traditional distributed architecture (also called the federated architecture), where each function has its own independent computing resource, the integrated architecture consists of a network of standardized computing modules each capable of supporting multiple functions at different criticality levels. According to the integrated architecture principles, the applications are updated or moved from one computing module to another without loss of functional and time correctness, possibly even through a dynamic reconfiguration. This is achieved with common interfaces to hardware and network resources and through *protection mechanisms* that enable functional and time encapsulation.

In the automotive industry, the AUTOSAR (AUTomotive Open System ARchitecture) partnership among equipment manufacturers and software suppliers was recently created as a move towards integrated architectures [34]. Whereas in avionics the rationale behind the integrated architecture is to reduce the number (and weight) of control units, in the automotive industry it is rather to decouple an exceptionally high growth rate of software functions from the growth rate of control units. A significant AUTOSAR goal is the definition of a standard for software components that can execute independently from their placement on the set of distributed electronic control units. As such, the standard has so far been developed focusing on portability and reusability of components. During the design phase AUTOSAR components are logically connected over the *virtual function bus*, which is implemented through a very complex run-time layer that provides location independence.

Nevertheless, in safety- and time-critical systems, location independence is not the only concern. Instead, the control of the *system-level behavior* that emerges from the cooperation of components becomes a priority. In AUTOSAR, the activation and synchronization semantics among components is specified using run-time layer events that are local to each *electronic control unit* (ECU) [9]. This makes difficult the realization of a system-level semantics, as well as any system-level simulation and verification. Thus, AUTOSAR tools are currently used in conjunction with other tools, which leads to various problems with heterogeneous modeling and design. Another issue is that AUTOSAR still lacks a *well-defined concept of time*, which is necessary for any formal reasoning about system behavior. As a consequence, its event model does not allow the definition of synchronization among timed events [9]. The time model is indeed briefly addressed in Section 5 of Virtual Function Bus Specification (version 3.1.) [34], but it is not yet part of the standard.

Looking more closely at the power systems IEC 61850 and automotive AUTOSAR standards,

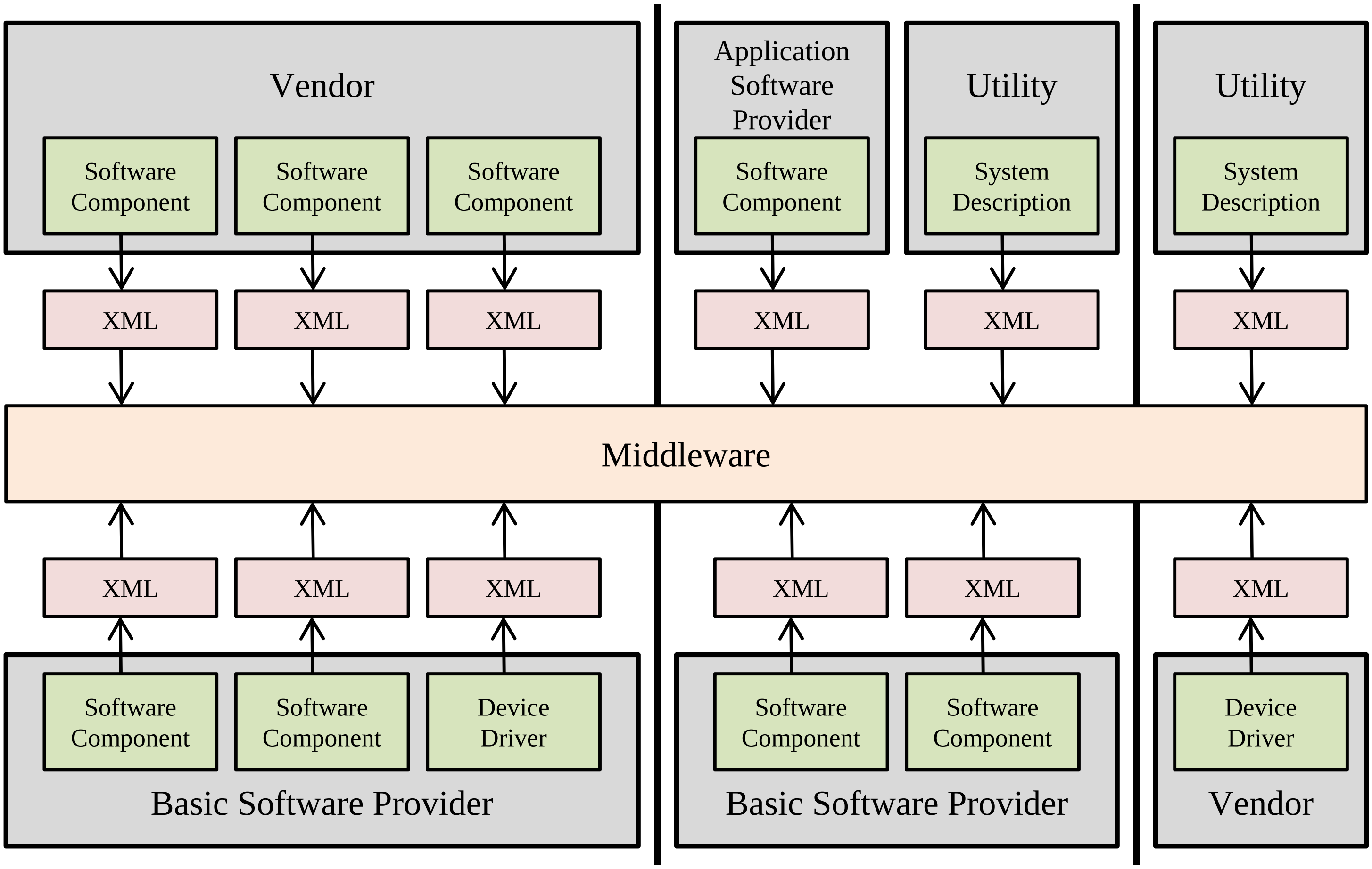


Figure 2: Integration of software components with spatial and temporal partitioning

certain parallels can be drawn between the intended design of distributed applications in two industries. For instance, IEC 61850 logical node, logical connection and physical device concepts are analogs of AUTOSAR software component (also called runnable), virtual function bus, and ECU respectively. Even device configuration files written in XML-based substation configuration language of IEC 61850 look similar in function and scope to ECU description files of AUTOSAR. However, IEC 61850 is a standard created primarily to facilitate communications between power devices in electric substations. As such, not enough attention is given to applications developed by different vendors and with different criticality levels that have to execute on the same hardware. To tackle this, we propose the protection mechanisms of the integrated architecture. These mechanisms partition the system into execution spaces and prevent unintended interference of applications. They are especially needed if the safety-critical and non safety-critical applications coexist. Fig. 2 gives an example of software component integration on a single processing device with thick line denoting partition boundaries.

Moreover, considering the current AUTOSAR status, if a more formal programming model for the software components is not adopted we foresee similar integration issues with IEC 61850. Namely, we predict problems with the control of system-level behavior and verification of properties related to timing constraints. Note that timing constraints in some substation or microgrid automation applications can be severe. Although IEC 61850 defines the highest rate of 256 samples per power system cycle for power quality applications, some resampling algorithms require a rate of up to 1000 samples per cycle (10μs order). In addition, network messages with critical triggers often require transmission times below 3ms, whereas time synchronization accuracy requirements can be as small as 1μs.

2.2.3 Approach

In this subsection we sketch a potential approach for introducing timing semantics into the design and deployment of distributed applications. The author is directly involved in a project to which we refer an interested reader for more details.

Most real-time software is structured as tasks with periods or deadlines. In [37] we proposed an alternative programming model called PTIDES (Programming Temporally Integrated Distributed Embedded Systems). This programming model leverages network time synchronization [13] to provide a coherent global temporal semantics in distributed systems. PTIDES is an extension to the Ptolemy II simulation environment [14]. It is based on the semantics of discrete-event (DE) systems [3, 4], which provides a model of time and concurrency. PTIDES actors are concurrent components that exchange time-stamped events via input and output ports. The event time stamps are a formal part of the model referred to as model time. Model time may or may not bear any relationship to time in the physical world, i.e., real time. In typical DE semantics, each actor processes input events in time-stamp order but without constraints on the real time at which events are processed. PTIDES extends DE by establishing the correspondence between model time and real time at sensors, actuators, and network interfaces.

In [38] we give an execution strategy for PTIDES deployments and introduce feasibility analysis. The PTIDES design flow is presented in [12, 11] using power plant emergency detection and power supply shutdown as application examples. Figure 3 shows the high level model of the power plant emergency detection application. In [22] we evaluate a PTIDES deployment on a synchrophasor based application. Synchrophasor measurement units sample voltages and currents at diverse locations on a power grid and output accurately time-stamped measurements together with phasor angles. The evaluation in [22] is based on experiments on a system of distributed time-synchronized micro-controllers and an emulation of portions of the electric power grid based on conventional hardware-in-the-loop instrumentation. We believe that the PTIDES design environment can serve as a semantic basis for an integrated architecture for smart grid applications.

2.3 Business Model Considerations

The integrated architecture is a solution to increased software-related costs and quality problems. The cost is commonly attributed to two factors: high software development expenditures and elimination of software errors during maintainance. The lack of software reuse that is common in the traditional architectures implies both that similar applications are developed more than once and that each is tested insufficiently to guarantee quality. On the other hand, an industry pool gathered around an integrated architecture cooperates on a software standard, but competes on implementations. The hardware and low-level software components are seen as commodities, and the focus is on the development of innovative and competitive applications. Thus, a general benefit of the integrated architecture for all players is increased *reuse of software* (especially low-level). This reduces development costs and the amount of errors, which, in turn, results in fewer software-related recalls. In addition, transparent and clearly defined interfaces enable outsourcing and other new business models.

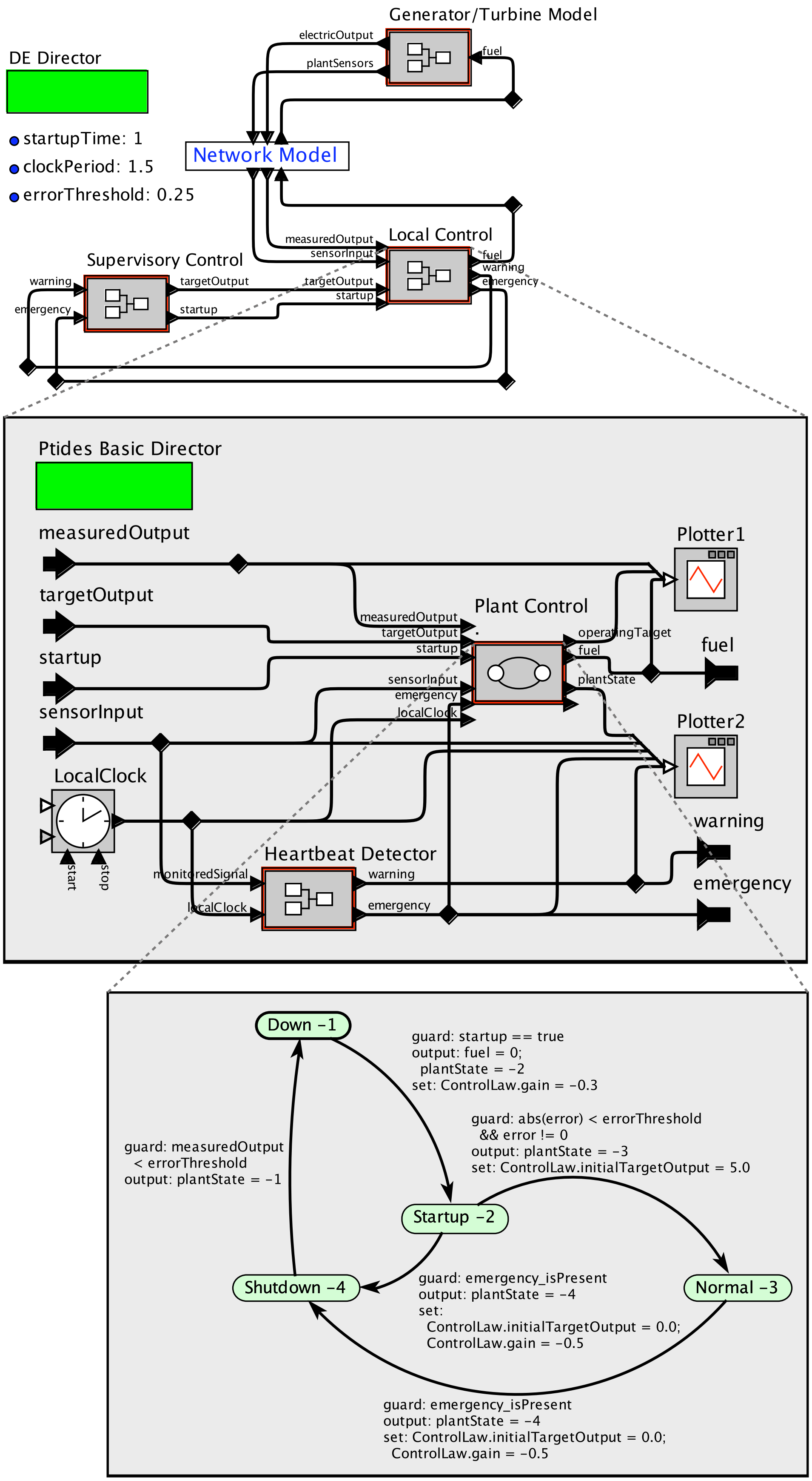


Figure 3: Model of a small power plant. This model can be opened, run, and even modified by clicking on the figure above (if you are reading this on a computer), or by going to `http://ptolemy.org/PowerPlant` on a Java-capable machine.

In the automotive industry, an AUTOSAR partnership includes collaboration between a car maker (e.g. BMW), a tier-1 company (e.g. Continental AG), software providers (e.g. NavNGo), tool developers (e.g. dSPACE) and hardware providers (e.g. STMicroelectronics). A typical AUTOSAR business model would have the tier-1 as the integrator of ECUs. The tier-1 would purchase a micro-controller from a hardware provider, design low-level software components and merge them with hardware and often some middleware. On the other hand, for many applications the car maker serves as application software integrator after purchasing them from a software provider(s). There are cases where the car maker serves as a full application software integrator, but no cases where car maker is the hardware or low-level software integrator. Final software integration and ECU delivery are typically done by the tier-1 company, whereas vehicle assembly by the car maker.

In the power systems industry, utilities and vendors correspond to car makers and tier-1 companies respectively. However, the collaborations in this sector presently tend to have fewer parties. This is typically carried out in the federated architecture style, i.e., for a given controller unit project, the utility collaborates with a given vendor on the complete controller unit implementation. Very often, this looks like a classical black-box business model, with no transfer of intellectual property between vendor and utility. For instance, in a recent utility-scale wind farm project, the energy company First Wind used as storage the dynamic power resource technology developed by Xtreme Power [25]. This storage company, in turn, used services of a software contractor (Jennings Embedded Services), who based its implementation entirely on tools and hardware from National Instruments. As the smart grid market develops, we expect these linear partnerships to be replaced with truly integrated collaborations. A potential cooperation diagram is shown in Fig. 2.

The rest of the section addresses potential business cases and benefits of the integrated architecture for all main stakeholders, including utilities, vendors, regulators and consumers.

2.3.1 Utilities and Microgrid Owners

The integrated architecture enables application partitioning and correct distribution over processing units. As explained in Sec. 2.2.1, this can increase *reliability* of power equipment and subsystems. In principle, this would result in less frequent repairs, faster response to outages, and thus, better customer service. However, as discussed at length in [1], utilities find difficult to come with viable business cases for distribution automation reliability. This is so because the costs of required advanced switching and communication technologies still exceed the costs utilities would avoid with the reliability upgrades. This is even despite the fact that such upgrades do not require consumer education or behavior change.

In the U.S., most utilities have yet to standardize on the IEC 61850 standard. Paper [19] notes how up to this time the standard has been more popular elsewhere in the world. This is explained by differences in substation acquisition and maintenance policies. The North American utilities tend to keep control over the maintenance of their facilities. Thus, the savings in substation wiring and configuration are offset by the costs such as maintenance personnel training. In addition, the North American utilities prefer to have facility equipment supplied by multiple vendors. As it becomes necessary for the multi-vendor equipment to communicate with each other, the demand for using IEC 61850 will increase. Now, when even the software components supplied by different vendors become *interdependent* in order to achieve complex functions on the same unit, the need for the integrated architecture methods will be more obvious. For instance, a utility can decide to buy outage management software from one supplier, but supervisory control and data acquisition software from another. The approach also allows *upgrading* or adding more functions without new grid infrastructure costs.

In addition, utilities can also work with vendors to integrate applications and services creating their unique brand value. Therefore, as we are already seeing with consumer electronics manufacturers and car makers, utilities will be relying more and more on software to *differentiate their services*. This becomes especially relevant in the deregulated supply system, where generation and distribution are separated, and consumers are free to purchase from any suppliers on the grid.

2.3.2 Equipment Vendors, Software and Service Providers and Integrators

In the integrated approach, an equipment vendor would most likely serve as a system integrator. It would develop a platform of hardware and software components and then work closely with the utility to integrate the utility's value-added intellectual property on top of such a platform. The vendor would typically have complete control over the cooperation, communication and synchronization among subsystems and functions, which would enable architecture optimization and better control over the system-level behavior. However, to some degree it would be replaced by pure software providers. To counter this effect, it must acquire high levels of expertise in *both software design and integration*. We have already seen this trend with recent acquisitions by GE (Opal Software) and Schneider (Televent).

Beside the already discussed benefits such as the reduction of software development time and cost, the vendor can share its software modules with other vendors, or reuse and sell non-competitive modules to multiple utilities. A part of business can come from *tool development*, e.g. automatic code generators from component interfaces or application behavior models. Since the entire exchange between different parties is based upon specifications, the vendor can also serve as a *conformance agency* that would be verifying whether software implementations meet required specifications. Finally, it can provide *services*. For instance, although the above mentioned company Xtreme Power sells its dynamic power resources as systems which include software and controls, the similar storage systems are sold as services.

The integrated architecture puts higher demand on license issues and agreements. No single utility or vendor will be influential enough to attract application developers to their proprietary solution. Therefore, *open source software* is a plausible option for vendors because it provides greater flexibility and opportunities for innovation. Such an open source platform should be using technologies that developers are familiar with and have direct access to. In the automotive industry, we have recently seen this materialize with the formation of Genivi consortium [33]. Namely, led by a car maker (BMW), a tier-1 company (Magneti Marelli), an operating system provider (Wind River) and a silicon vendor (Intel), a Linux-based platform for in-vehicle infotainment software was put forward. In the smart grid arena, a communications platform and applications environment was announced for late 2011 by the SmartSynch company [32]. This environment will be based on the popular Brew programming kit for smart phones and cellular networks. It will come with an application store, where software providers and utilities will trade applications. The demand response and mobile workforce management are examples of expected applications. It remains to be seen whether this platform is broad enough and whether it can be used for other types of applications.

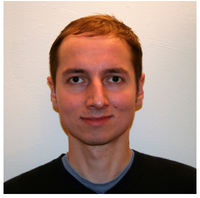
2.3.3 Regulators and Consumers

In the U.S., different states are at different stages of electric utility deregulation [26]. Utility deregulation is one reason for the increased interest in distributed energy resources. Thus, retail competition often gives rise to grid modernization. On the other hand, modernization can also make it easier for regulators to approve retail competition. In particular, in order to meet policy goals, regulators need better tools to measure *policy compliance* by utilities. For instance, in order to reduce carbon emissions, regulators would like to be able to measure energy efficiency of a utility, so that its regulated rate can be set accordingly. Note that in the traditionally regulated markets utilities have no financial motivation to increase energy efficiency.

The same applies to grid reliability and other so-called *social benefits*, provision of which utilities presently find hard to justify economically. The role of social benefits was first discussed in [23] where it is noted: "Quantifying societal benefits requires sorting these streams of benefits in a way that characterizes them by the source so that proper value transformation function can be applied. If this is accomplished, then benefits arising from different sources may be monetized and accumulated to provide an overall measurement of benefits." We believe that the integrated architecture, with its clear interfaces between various applications, will enable this characterization. In principle, it should be possible to determine how much each service provider contributed to the social benefit.

Ultimately, using the integrated architecture technology, the competition between power system players will refocus on *product innovation*. Thus, it will enable faster development of systems with increased complexity at reasonable costs with higher value as perceived by the final consumer.

3 Short Biography



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