Real-time and Interoperable Software for Smart Grid Mission-Critical Functions using Open-Source Platforms

CARLOS E. URIBE-BLANCO, VICTOR ALVAREZ-CORTES, ALFREDO ESPINOSA-REZA
Dirección de Tecnologías Habilitadoras,
Instituto Nacional de Electricidad y Energías Limpias,
Reforma 113, Col. Palmira, Cuernavaca, Morelos,
MEXICO

Abstract: - A coherent proposal is presented, delineating the essential characteristics that must be met by a real-time and interoperable software solution that encompasses the critical functions of the smart grid, particularly through the utilization of open-source platforms. The document presents several potential development options, platforms, and open-source software; its primary objective is to provide the reader with a set of considerations for decision-making regarding the purchase or development of a software product of this type, as well as the minimum criteria that should be considered when choosing a full development option. The document reflects the author's experience.

Key-Words: - Real-time software, interoperability, smart grid, mission-critical software, open-source platforms, SCADA, Grid Monitoring, Grid Control.

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1 Introduction

In 2012, the Smart Grid was described [1] as "an advanced power grid for the 21st-century; hinge on adding and integrating many varieties of digital computing and communication technologies and services with the power-delivery infrastructure". It also includes "Bidirectional flows of energy and two-way communication and control capabilities will enable an array of new functionalities and applications that go well beyond «smart» meters for homes and businesses". The 2021 version of [1] and [2], obviates a definition of Smart Grid; instead, it states, “Because electricity is perishable, most power is delivered at the time it is generated. The supply, transmission, distribution, and electricity consumption in the system are therefore closely coupled, and must be actively coordinated”, and continuous “This requires the coordinated sensing, measurement, and control of devices and systems spread across the grid”.

Nowadays, the Smart Grid definition is a well-established concept related to grid modernization, adding intelligence, monitoring, and control to the classical power grid. Most countries have many functions deployed related to grid modernization, and those countries are finding the next steps to optimize energy and cost, considering new concepts such as climate change, global heating, and social justice.

1.1 Literature Review

Some classic Smart Grid functions have been well accepted, established, and implemented, like Advance Metering Infrastructure (AMI), Meter Data Management (MDM), Customer Information Systems (CIS), Geographic Information System (GIS), and Data Acquisition and Control (DAC), among others. To outline Smart Grid technologies and identify the top solutions adopted [3] establishes a benchmark.

Other advanced smart grid functions have been implemented on a slower curve, some functions such as Advance Distribution Management System (ADMS) or Big Data and Analytics (BDA), probably because of the cost, quality of data, and effort required.

In [4], the authors provide an overview of Smart Grid technology, specifically focusing on the challenges presented by cybersecurity, interoperability, and renewable energy integration. These aspects were determined to be the most prevalent issues facing the advancement of Smart Grids, specifically for global application.

Artificial Intelligence, blockchain, and cybersecurity are new abilities incorporated into Smart Grid applications, in this sense; [5] presents a review of the state-of-the-art integrated artificial intelligence and blockchain-enabled scheduling, management, optimization, privacy, and security of the smart grid and power distribution automation.

Data drives Smart Grid, communications, and the ability to make new and better decisions based on information and inherent knowledge. If this knowledge cannot be retrieved efficiently, it remains stagnant in information warehouses, resulting in a wasted capacity within the electric utilities. [6] presents a proposal for the architectural components that enable the organized and collaborative request, transport, and effective utilization of large volumes of historical information. That proposal does not compromise the performance of the information systems and the supporting technological platform; additionally, shows the use and adoption of the Common Information Model (CIM) as defined in the IEC 61968 and IEC 61970 standards.

2 Problem Formulation

Some advanced Smart Grid functions require long-term planning. Specialized personnel normally are not available, and costs require multi-year budget management. In addition, some technical features are not easily accessible with traditional solutions. In this sense, a utility has at least two options:

1) Buy established commercial products and pay for licenses to use them.
2) Develop an entirely new product, including functional and non-functional specifications.

The overwhelming majority of electric companies select option (1) due to the inherently complex nature of the functions to be implemented. The development of these functions necessitates the involvement of highly specialized personnel, infrastructure, experience, and seamless long-term technical support, all of which are challenging to comply with strictly. This section describes some specific features of Smart Grid's advanced functions.

2.1 Real-time Applications

This category of applications encompasses those that engage with their surrounding physical environment and respond to environmental stimuli within a specified temporal window. In the Smart Grid context, it is fundamental that the response to any request, query, command, or data transfer, is executed expeditiously, with deterministic response times (dependent upon the medium, protocols, and communication devices utilized). This allows users to make well-informed decisions based on the most current information, regarding the status of the physical equipment. Some of the real-time applications for smart grids include:

- Distribution Automation (DA) and substation automation (SA).
- Fault Detection, Isolation & Restoration (FDIR).
- Grid Monitoring and Control (SCADA).
- Protection & Safety.
- Volt and VAR Control (VVC).
- Power Quality (PQ).
- Demand Response Management (DRM).
- Phasor Measurement Units (PMUs).

Smart Grid applications can be described using the Smart Grid Architecture Model (SGAM) defined in [7], as shown in Figure 1.

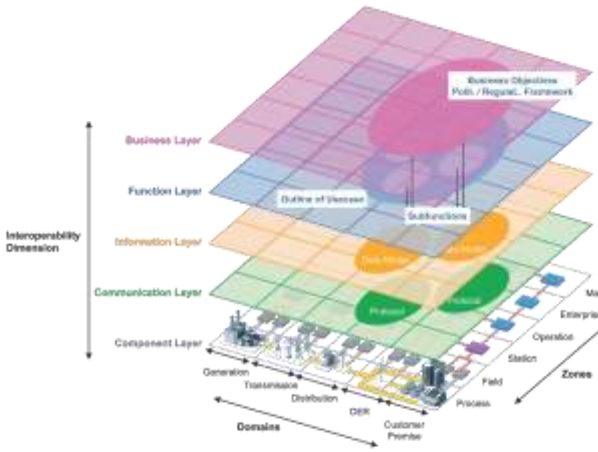


Fig. 1: The Smart Grid Architecture Model (SGAM) is defined in [7]

2.2 Semantic Interoperability

In [2] authors define interoperability as “the capability of two or more networks, systems, devices, applications, or components to work together, and to exchange and readily use information — securely, effectively, and with little or no inconvenience to the user”.

Semantic interoperability is defined in [8], establishing three categories of interoperability (Technical, Informational, and Organizational), the informational category is based on two-layer levels, the business context and semantic understanding.

In the informational/semantic category, any information model (ontology) can be used, provided it meets the requisite characteristics common to all utility systems. The necessity for semantic interoperability demands the implementation of a data model to facilitate efficient information exchange between domain systems. This data model should include the ability to receive and send messages validated in the syntax (format) and semantics (meaning) defined for the exchange [6].

SGAM considers the semantic interoperability and data models at the Information Layer (Figure 1).

2.3 Mission-critical Functions

An information system tasked with mission-critical functions is characterized by unique traits, resulting from the specific nature of its tasks.

The most relevant characteristics are as follows:

- Deterministic real-time response. The system performs operations at fixed time points or within fixed time intervals, irrespective of operational or functional conditions.
- Schedule tasks. Assign resources based on their priority, arrival time, and timing requirements.
- Fault tolerance. Monitoring the status and performance of applications and the system, taking remedial actions if a fault is identified.
- Redundancy. Ease of changing processes or threads very quickly, even replacing all processing using a secondary instance that runs in parallel (hot-swap).
- High availability. Ease of always being operational, regardless of the number of users and tasks, the system must always respond appropriately.
- High performance. Ability to process bursts of thousands of interruptions or events per second, without losing.
- Communication mechanisms. Data exchange between tasks (queues, threads, semaphores, events, etc.), as well as externally with other elements of the integrated system or other systems, applications, modules, consoles, screens, users, devices, sensors, and actuators, among others.
- Managing interruptions and timers. Activating or suspending tasks according to the needs of the system.
- Error management. Detect possible errors or abnormal behavior and take action to remedy them.

For Smart Grid, the classic mission-critical applications are the SCADA systems, and the Energy Management Systems (EMS).

3 Problem Solution

The development of Smart Grid advanced functions necessitates compliance with specific features as outlined in Section 2 of this paper. In particular, a SCADA or EMS solution must comply with the three aforementioned features and consider the two options for obtaining the necessary resources: purchase or development.

This section presents open-source platforms as a potential solution for the development of Smart Grid advanced functions.

3.1 Open-source Platforms

Open-source software (OSS) is a comprehensive set of high-performance and enterprise-level products that includes the following features:

- It is distributed under a license that allows users to use, study, modify, and redistribute it freely.
- Offer great flexibility and control over the technological environment.
- It is generally cost-free to use.
- Allows to adapt and customize solutions according to their specific needs.
- Users can examine the code to identify and fix security vulnerabilities.
- A collaborative community supports and backs solutions.

When selecting an open-source platform to develop real-time, interoperable, and mission-critical software, several components must be carefully chosen for their relevance to the final product:

1) Operating System. A real-time operating system (RTOS) is a type of software that oversees the management of a computer's hardware and software resources, ensuring the timely completion of tasks within specified time constraints. These systems are used in contexts where a high volume of data and events are processed. Representative examples of RTOS include VxWorks, Solaris, QNX, Spectra, FreeRTOS, and several variants of Linux and UNIX.
2) Programming language. It must be appropriately selected to achieve the characteristics described in Section 2. Any of those found in the first places of the TIOBE Index [9] are candidates, but their specialization and compatibility must be evaluated.
3) Infrastructure for message management. To achieve the high level of performance required, it is necessary to include a component of this type. There are several such

components, including RabbitMQ, ZMQ, Apache Kafka, NSQ, BlazingMQ, and others.

4) Real-time database. This component is crucial to establishing real-time data communication mechanisms, and these components usually reside only in volatile memory. Several products are available, for example: Redis, KeyDB, RethinkDB, Apache Druid, Apache Pinot, ClickHouse, and Aerospike.
5) Historical database. Many products can be adopted for this function, from traditional SQL to NoSQL, from traditional SQL to NoSQL. The selection should consider the product's functional support, robustness, and ability to process a large amount of time series. Some traditional and well-established products are MongoDB, PostgreSQL, MySQL, MariaDB, CockroachDB, Cassandra, Timescale, Firebird, Neo4j, and CouchDB, among others.
6) Configuration database. With lower performance requirements than the historical database, the selection should consider the ability to handle composite data, complex data, and geospatial data efficiently. Some possibilities include specific extensions on traditional database products: MongoDB with GeoJSON, and PostgreSQL with PostGIS. If a map server is a requirement, consider components such as GeoServer, MapServer, or QGIS.
7) Graphical user interface. This area offers many possibilities, and a large number of components and technologies that can be leveraged, ranging from vector graphics management to business intelligence tools. Some of the most widely used components include Bootstrap, Foundation, Angular, Ecma Script, HTML5, CSS, GoJS, Grafana, and Pentaho, among others.

3.2 Infrastructure

The infrastructure will facilitate the proper functioning of the technological architecture within established parameters. To ensure the efficient execution of the various applications and services, it is recommended that infrastructure components, including those for monitoring physical resources, be implemented. The most popular options are Kubernetes, Docker, OpenShift, Apache Mesos, Prometheus, Apache HTTP Server, and Ansible.

3.3 Knowledge and Experience

The development of real-time, interoperable, and mission-critical software requires the input of a group of specialists in various technologies, who possess the requisite knowledge and experience to provide effective guidance throughout the development process. It is recommended that the following specialized roles be included:

- Project manager.
- Technical architecture.
- Software architecture.
- Leader in the problem domain.
- Leader in open-source applications.
- Real-time operating system expert.
- Communications protocols.
- User interface designer.
- Database administrator.
- Application Programming Interface (API) architecture.
- Testing and Configuration control.

3.4 Standardization

In the context of smart grid applications, standardization is a critical area of consideration, extending from the application architecture to the design of the graphical user interface. The most relevant standards to observe are:

- IEEE Std. 1003.1 for POSIX (Portable Operating System Interface).
- IEEE Std. 1815 for DNP3 (Distributed Network Protocol).
- IEC 60870/TASE.2 for ICCP (Inter-Control Center Communications Protocol).
- IEC 61968/IEC 61970 for CIM (Common Information Model).
- IEC 61968-100 for data interfaces CIM based.

3.5 Long Term Support

A product as described in this document typically has an average lifespan of 10 to 20 years, depending on the maintenance of the hardware infrastructure. During this period, technical support, maintenance, and improvements must be provided continuously and promptly. Therefore, an electric company that chooses to develop the product for its Smart Grid implementation should consider hiring specialized personnel within its organizational structure, so that it does not depend on contracts or people external to the company to keep the installed products running.

4 Results

This section describes the result of developing a real-time, interoperable, and mission-critical software product.

4.1 Use Case

The Smart Grid Use Case selected was "Grid Monitoring and Control"; for this Use Case, a real-time and interoperable software for mission-critical functions was defined, and specificities to using open-source platforms.

The operational context for the selected Use Case can be described in the SGAM Component Layer [7] as shown in Figure 2.

All the concepts, recommendations, and features described were documented and applied.

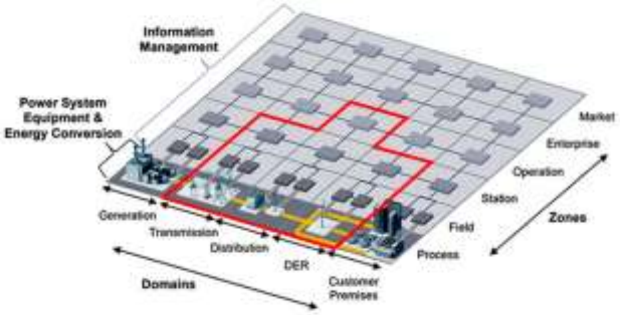


Fig. 2: The context for the selected Use Case (in red), "Grid Monitoring and Control", is based on SGAM, [7]

4.2 Testing Results

The final product developed was tested considering a database for 150,000 remote points to monitor for real-time communications.

The user interface includes:

- At least 10 concurrent users, for operations and configuration.
- Applications monitoring for error detection.
- Mobile application for remote supervision.
- Protocols communications statistics for operations reliability.

The Testing Cases include:

- Alarm tsunami for 500 in a second.
- Real-time monitoring for Digital, Analog, and State values.
- Response time and re-tries, for field devices.
- Concurrency.
- Accuracy.
- Historical data logging.
- Standardized graphical user interface.

DNP3 protocol conformance test, [10]:

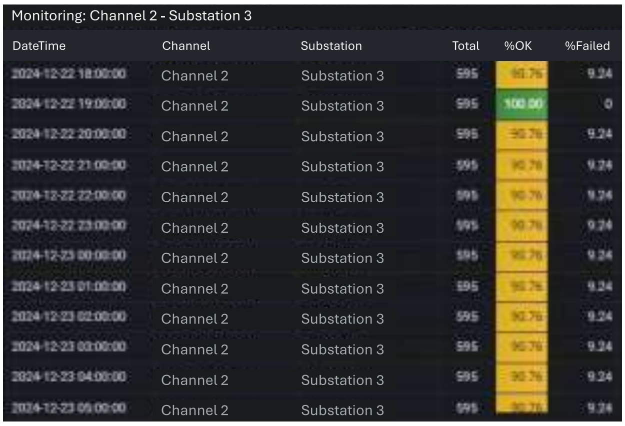
- All the Level 2 implementation was tested.
- The conformance test was performed according to the DNP Intelligent Electronic Device (IED) Certification Procedure.
- Test procedures version: 2.7.
- The test was scoped based on the following document: TMW SNDP Library Device Profile version 3.20.000 dated 2016-04-03.
- The Certificate of Conformance was obtained by DNP Group.

The software product developed for monitoring and controlling an electrical network, considering the described characteristics, was rigorously tested in a laboratory specifically designed to validate each Use Case, Test Case, function, and component. Communication protocols were integrated and those developed internally were certified according to the relevant standards. Remote device simulators were employed to validate the sequences of automatic commands. The software is installed and operational in multiple real-world settings, overseeing and regulating the electrical grid supplying electricity to entire cities. Several enhancements and upgrades have been implemented, and there are ongoing plans to sustain functional advancement for several years.

Figure 3 shows a graph of real-time communication statistics (performance) for two DNP3 protocol channels of an implementation of the product developed for monitoring and controlling an electrical network.

Fig. 3: Channel communication statistics for 2 power substations using DNP3 protocol

Figure 4 shows cumulative communication statistics (reliability) for a DNP3 protocol channel of an implementation of the product developed for monitoring and controlling an electrical network.


Monitoring: Channel 2 - Substation 3

DateTime	Channel	Substation	Total	%OK	%Failed
2024-12-22 18:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-22 19:00:00	Channel 2	Substation 3	595	100.00	0
2024-12-22 20:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-22 21:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-22 22:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-22 23:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-23 00:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-23 01:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-23 02:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-23 03:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-23 04:00:00	Channel 2	Substation 3	595	90.76	9.24
2024-12-23 05:00:00	Channel 2	Substation 3	595	90.76	9.24

Fig. 4: Channel communication statistics for 1 power substation using DNP3 protocol

Figure 5 shows some hardware statistics (server availability) of a real implementation of the product developed for monitoring and controlling an electrical network.

Fig. 5: Server statistics in a real-world application

4.3 Future Works

In future works, the plans include integrating new functions for advanced data analytics (such as autonomous pattern detection, automatic responses, prediction, new enterprise information exchange, and abnormal function detection) into existing or new products; additionally, new Smart Grid functions will be incorporated, including Distribution Operations and Modeling Analysis (DOMA).

5 Conclusion

The development process of real-time and interoperable software for Smart Grid mission-critical functions presents a significant challenge. To meet and comply with the definition and specifications, it is essential to have all the necessary elements in place, as well as the infrastructure, technical support, human and financial resources, and a strategy that allows for the establishment of a work program following the commitments and milestones that have been established.

It is a feasible undertaking. As the Chinese philosopher Lao Tzu said, "The journey of a thousand miles begins with one step". The key is to combine the relevant elements described in this article and make the right decision at the right time.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Carlos Uribe, technical leader, real-time applications expert, and senior developer.
- Victor Alvarez, open-source expert, components evaluation and selection, and senior developer.
- Alfredo Espinosa, leader in the problem domain, resource manager, enterprise relations, and quality control.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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