Distributed Power System Automation with IEC 61850, IEC 61499 and Intelligent Control

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Abstract. *This paper presents new approach to power system automation, based on distributed intelligence rather than traditional centralised control. The paper investigates the interplay between two international standards, IEC 61850 and IEC 61499, and proposes a way of combining of the application functions of IEC 61850-compliant devices with IEC 61499-compliant "glue logic," using the communication services of IEC 61850-7-2. The resulting ability to customise control and automation logic will greatly enhance the flexibility and adaptability of automation systems, speeding progress toward the realisation of the Smart Grid concept.*

Keywords: Power system automation, IEC 61850, IEC 61499, Smart Grid.

I. INTRODUCTION

A significant challenge now confronting the Electricity Industry is that proven architectures based on 20th century performance requirements are now looking increasingly antiquated. The need to fundamentally change the architecture and performance of electricity networks has risen quickly to the fore in developed economies, as a result of concerns about:

- Energy security. The combination of dwindling low-cost energy sources (in some parts of the world), and the vulnerability to terrorist disruption of existing energy supply systems means that more resilient energy infrastructure is desirable.
- Global warming and greenhouse gas emissions. Replacement of fossil fuels with flexible, renewable and distributed energy resources brings a raft of operational problems which cannot be solved with existing technologies.
- International competition. The preservation and enhancement of traditional comforts (employment, community services, etc.) in developed economies depends on successful competition in international marketplaces, and this in turn depends (at least in part) on "digital quality" electrical power.
- Market failure. Customer demand response to market prices is all but absent in deregulated electricity markets. New technologies are needed to facilitate end-user participation in electricity markets.
- Performance of network service providers. As regulated monopolies, such companies must strive to meet ever higher performance expectations in an economically efficient way. New technology can help to improve performance while containing costs.
- The digital society. Private individuals increasingly rely on "digital quality" electrical power to serve their lifestyle needs.

The agendas for technical reform are crystallised in EPRI's IntelliGrid Architecture [1] (for North America) and the European SmartGrids Technology Platform [2] (for the European Union). The most complex initiatives require significant research and development effort prior to commercialisation.

In this paper a new approach to power system automation is proposed aiming at the challenges listed above. It is based on the ability to automatically detect changes and reconfigure the power system appropriately. The proposed solution aims at making power system automation more adaptable to uncontrolled environmental influences such as:

- Network topology - growth and/or alteration of the network to cater for changing loads;
- Network loads and embedded generators - coming and going in response to energy pricing signals;
- Nature of loads - critical (e.g. hospital), industrial, domestic;
- Weather - affecting conductor ratings, the level of solar PV and/or wind generation, etc.
- Primary system failures - cars hitting poles, builders digging up cables, equipment failing;
- Secondary system failures - loss of monitoring and/or control, errors in measurements, etc.
- Source impedance - affecting voltage profiles and fault levels.

Two upcoming international standards IEC 61850 and IEC 61499 make the backbone of the proposed automation architecture.

The paper is structured as follows. In Section II the state of the art in power system automation is briefly surveyed. Section III discusses the IEC 61850 standard's role in achieving flexibility of automation via interoperability of components. Section IV presents the idea of implementing the control logic of automation systems using IEC 61499 function blocks. In Section V we further investigate the potential interplay between the two standards using examples of automation and monitoring functions. Section VI shows a scenario in which fault location, isolation and supply restoration are accomplished by collaborating distributed components. Implementation of the corresponding distributed simulation with IEC 61499 function blocks is sketched in Section VII. The paper concludes with future research plans and References.

The factual references in this paper often come from ENERGEX, one of Australia's largest power distribution utilities.

II. POWER SYSTEM PROTECTION AND AUTOMATION

A. *Power system equipment*

The typical ENERGEX customer is supplied via a *service wire* from a three-phase, *LV (low voltage) distribution feeder* with a nominal voltage of 240 volts (phase-to-neutral) / 415 volts (phase-to-phase). As exemplified in Figure 1, each LV feeder is supplied by an 11kV/415V *distribution substation*, typically a pole transformer or ground transformer. Each distribution substation is supplied via a *MV (medium voltage) distribution feeder*, with a nominal voltage of 11kV (phase-to-phase), from a *zone substation*. Each zone substation is supplied via a 33kV or 110kV *subtransmission network* from a *bulk supply substation*. Each bulk supply substation constitutes an interface to the *transmission system*.

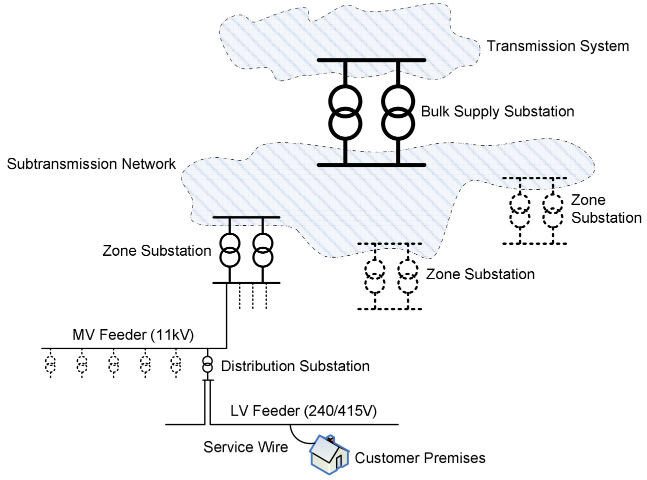


Figure 1. Typical residential electricity supply structure.

In urban and rural settings, LV feeders and 11kV feeders typically have a *radial* configuration, meaning that each has a single point of supply – a distribution substation or a zone substation, respectively. *Paralleling* of, and *load transfers* between, adjacent feeders may be effected via *ties*.

Feeders may be of *overhead* or *underground* construction. Overhead feeders comprise four (LV – three phases plus neutral) or three (HV – three phases only) open wires on ceramic or synthetic *insulators*. Underground feeders comprise *cables*, either *direct buried* or in *conduit*.

ENERGEX manages approximately 300 zone substations. Per zone substation there are typically 6-12 11kV feeders, 80-150 distribution substations and 5 000-10 000 customers.

B. *Protection*

After supplying customers with electricity, the foremost mission critical function of the distribution system is *protection*, i.e. the detection and clearance of *faults* and *overloads*. A fault is defined as the uncontrolled flow of electrical energy due to insulation failure. To put things into perspective, human contact with a live 11kV conductor is usually fatal. Fault currents at 11kV are up to 20kA; hence the energy released at the site of a fault can be highly injurious to both humans and equipment.

The simplest form of protection is *fuse* protection, but for a range of reasons this is used only at the extremities of the network. Elsewhere, faults are detected by *protective relays* and cleared by *circuit breakers*. A protective relay processes voltage and current measurements in order to determine the existence, and also in some cases the location, of a fault.

A circuit breaker is a type of *switch* capable of interrupting fault current. Other switch types with less onerous capabilities include *load break switches* (capable of interrupting load current but not fault current) and *disconnectors* (only capable of off-load switching for the purpose of isolating equipment for maintenance access).

Faults on 11kV overhead feeders can be temporary in nature, e.g. caused by tree branches or animals. Accordingly the associated feeder circuit breakers are often configured with *automatic reclosing*, a function which re-closes the circuit breaker one or more times after fault clearance in an attempt to restore supply. If the fault is permanent, a *lockout* occurs and the feeder cannot be put back into service until repaired.

To speed the process of restoring customers blacked out by a fault, an 11kV feeder may be divided into sections by *sectionalising switches*, and connected to adjacent feeders via (normally open) *tie switches*. Once the site of the fault has been located, sectionalising switches are opened to isolate the faulted section, and tie switches are closed to restore supply to the unfaulted sections.

C. *Automation*

Computer-based remote control of power system equipment simplifies such processes as restoring power to customers blacked out by a fault.

For example, control of sectionalising switches can be done by remote manual control using a *SCADA (Supervisory Control And Data Acquisition) system*. SCADA has been a feature of zone substations (and above) for at least three decades. With improvements in technology, SCADA has become cost effective for distribution system equipment as well.

Recently, automated *FLISR (Fault Location, Isolation and Supply Restoration)* products have begun to appear on the market. These products use the SCADA system as "eyes and arms" to gather information about faults and effect the necessary control actions (opening and closing of switches). In the most common architecture, FLISR is a subsystem of a centralised *DMS (Distribution Management System)*. This architecture leverages the existing role of the DMS as a repository for network-related data such as connectivity, equipment ratings and historical load records. One product (S&C IntelliTEAM II [3]) features an agent-based, decentralized architecture.

Both FLISR architectures rely heavily on SCADA data communications. The centralised architecture is more compatible with existing SCADA communications network architectures, which have traditionally been designed to support centralised monitoring and control. The decentralized architecture works best with peer-to-peer communications. In either case, cost effective communications with distribution equipment, widely dispersed on poles and in metal cubicles, has been and continues to be difficult to achieve.

III. INTEGRATION VIA STANDARDISATION

Protection systems are so critical that they have always been designed very conservatively. Wherever possible they are designed with *overlapping zones of protection* to ensure that any fault will be seen by at least two independent protective relays. Transmission system protection is usually designed with high degree of redundancy.

Only recently have protection engineers accepted the notion that protection, SCADA and local control functions can be integrated into a single, microprocessor-based device. Integrated solutions are appearing on two forms: "Smart" distribution switches, and integrated solutions for major substations.

Integration improves the capability and reduces the cost of distribution switches by allowing all of the protection and control functionality to be delivered on a single, purposed-designed circuit board, which is closely matched to the other components of the switch.

In major substations, integration improves capability and interoperability by allowing a redistribution of functions, once heavily dependent on heavy (110V / 5A) secondary wiring, across "smart" components which exchange information via a high speed data network. The leading standard in this area is *IEC 61850, Communication Networks and Systems in Substations [4].*

Tempering this evolution in secondary systems technology is the presence of an enormous "legacy" of old but otherwise perfectly functional (according to the original requirements) secondary systems.

IEC 61850 introduces various elements of the power-system-related automation architecture called Substation Automation System (SAS).

According to IEC 61850, a substation automation system can be represented in 3-layered form (Figure 2). The lowest, *physical* layer is implemented in intelligent end devices, such as circuit breakers, remotely operated switches, current and voltage sensors, and condition monitoring units for switchgear, transformers, etc. These are connected via communication channels to protective relays and bay control units that implement the protection, monitoring, control and automation tasks in a particular responsibility area (called a *bay*). On the top level of hierarchy there is the substation automation unit, which (*a*) integrates several bays within a substation, (*b*) implements the human-machine interface (with a human substation operator), and (c) communicates with control centre(s).

IEC 61850 defines a number of architectural artefacts intended to structure the intelligence of protection, monitoring, control and automation functions. These functions produce and consume signals that are usually communicated by thousands of wires – between the primary equipment and protection, monitoring control and automation devices. IEC 61850 defines so called data objects for the many real world signals, e.g. the circuit breaker position signal is defined as the data object with the standardized name *Pos.*

A capsule of data (e.g. *Pos*) and functionality (position indication of a circuit breaker) is called a *Logical Node.* The Logical Node that represents a circuit breaker has a standardized name *XCBR*. We may now think of a specific substation *Subs_ENERGEX_NMK* that has a circuit breaker 1042 (one of many). The reference *Subs_ENERGEX_NMK/XCBR1042.Pos.stVal* identifies the position of this circuit breaker. Any change of the circuit breaker position may be immediately communicated (via peer-to-peer communication) to other logical nodes, e.g. an instance of the Logical Node *CILO* (interlocking), protective relays, SCADA systems, etc.

In the case of CILO, the required input data (status information from a few or many switches) are communicated through IEC 61850. They are modelled as data objects of other Logical Nodes, e.g. XCBRs.

Several logical nodes can form the virtual analogue of a physical electronic device (e.g. a bay control unit). This is called a *Logical Device* and it can be implemented on a single physical device.

Thus, IEC 61850 can describe the interdependencies between the Logical Nodes within a device and beyond its borders (i.e. the use of communication over a network). Moreover, the functionality of the whole substation can be modelled by a collection of Logical Devices populated by Logical Nodes.

IEC 61850 does not define any internal details of Logical Nodes. For the interlocking node CILO, the standard just defines two data objects that represent the outputs of the interlocking logic: *EnaOpn* Enable Open and *EnaCls* Enable Close.

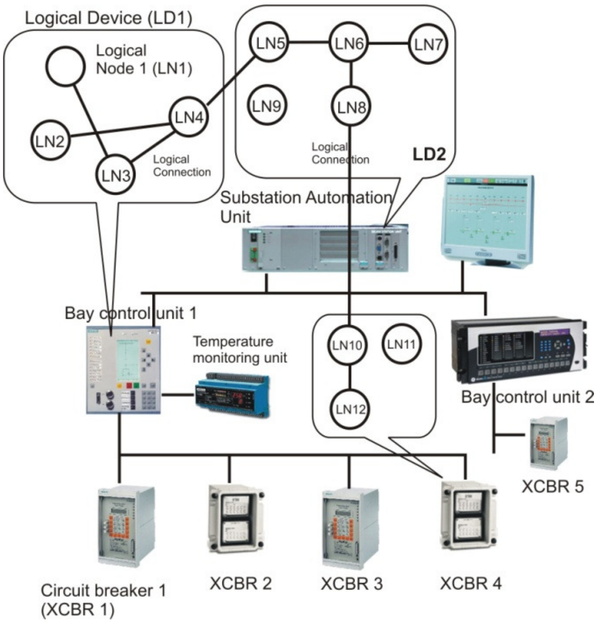


Figure 2. Physical and logical structure of the substation automation system according to IEC 61850.

Two functions for SCADA and condition monitoring are defined as built-in communication functions:

- Functions for supervising status values: Any change of a status value may issue a message (report) to a SCADA or other system or may post the changed value in a log (the log may be read later)
- Functions for supervising analog values: An analog value can be monitored for violation of absolute limits

(low-low, low, high, high-high, etc.) or relative limits (deadband, percentage change of the value). The limit violations may be reported or logged.

All of the devices shown in Figure 2 are digital computers having specific peripherals for switching high voltage circuits, or interfacing with other types of electro-mechanical actuators and sensors. The pieces of functionality (whose produced and consumed data are represented as logical nodes) are implemented in them as program code. IEC 61850 does not specify any details of such implementation. Vendors of such devices usually supply them pre-programmed, but with extensive configuration options.

IEC 61850 suggests the mechanism of system description called Substation Configuration Language (SCL) as defined in IEC 61850-6 [4].

A complete SCL file (the SCD file - Substation Configuration Description) contains all Logical Nodes and the communication links between them. The SCD file includes also the topology of the substation (breakers, transformers, lines between them, etc.)

A developer of substations can be interested in the following:

- Changing protection, monitoring, control and automation functions during the substation's life cycle. This may require the addition or deletion of logical nodes or logical connections, or modification of their internal structure and functionality.
- Re-using program components implementing the functions of Logical Nodes, or running them on physical devices of different vendors.
- Simulation of the whole substation. For that one would need a programmatic model of all the logical devices, populated by logical nodes and connected by logical connections. Unfortunately, vendors of different devices may use different incompatible hardware platforms, operating systems or programming languages for coding. They may also be unwilling to disclose the code at all. As a result simulation of the whole substation would be only partly possible.

The IEC 61850 standard is coming into wide use in the power industry. However, one area was intentionally left blank in the standard: IEC 61850 does not standardise the representation of combinatorial, sequential, rule-based (or any other form of) power system control and automation logic, e.g. the interlocking logic for determining whether a control operation (open EnaOpn=TRUE or close EnaCls=TRUE of a switch) can be performed or not.

The IEC 61499 standard [5], described in the next section, can fill this gap. This standard can be used to define the algorithms for a wide range of control and automation functions.

IV. ARCHITECTURE: IEC 61499 BELOW AND ABOVE THE IEC 61850

A. *IEC 61499 architecture*

The IEC 61499 standard [5] describes a general purpose *Function Block* architecture for industrial measurement and control systems. A Function Block is a software unit (or, more generally, an *intellectual property* capsule) that encapsulates some behaviour.

IEC 61499 defines three classes of function blocks: basic function blocks, composite function blocks and service interface function blocks. Each function block has a set of input and output variables. The input variables are read by the internal algorithm when it is executed, while the results from the algorithm are written to the outputs.

In IEC 61499 basic function blocks a state machine (called the Execution Control Chart, ECC for short) defines the reaction of the block to *input events*. The reaction can consist of the execution of *algorithms* computing some *output variables and internal variables* as functions of *input variables* and internal variables, and the emission of one or several *output events*.

A composite function block encapsulates a network of function blocks (both basic and composite), connected to the external data and event sources. The possibility to include composite FBs within other composite FBs enables a hierarchical system description. This is useful for defining multi-layered architectures. The FB-based architecture also enables modelling and simulation to be tightly integrated with the design process. Before deployment, the controller can be validated by either simulation or formal verification.

In the IEC 61499 architecture, the function performed by the system is specified as an application, which may reside in a single device or be distributed among several devices. The application consists of a network of function blocks connected by data and event connections. The control system is specified as a collection of devices interconnected and communicating with each other by means of one or more communication networks.

The use of function blocks makes the control device openly programmable and easily reconfigurable. IEC 61499-compliant devices can easily interface with each another, thus providing for seamless distribution of different tasks across different devices. The user may create his/her own program using standard function block types. Thus, the IEC61499 architecture enables encapsulation, portability, interoperability and configurability. Portability means that software tools and hardware devices can accept and correctly interpret software components and system configurations produced by other software tools. With interoperability, hardware devices can operate together to perform the cooperative functions specified by one or more distributed applications. With configurability, devices and their software components can be configured (selected, assigned locations, interconnected and parameterized) by multiple software tools.

B. *Implementing IEC 61850 provisions with function blocks*

The IEC 61499 architecture can provide solutions to the problems listed in the end of the previous section. The concept of a function block can be used to implement, in a vendor independent way, Logical Nodes and Logical Devices together with the functions that produce and consume the data objects of the Logical Nodes. This is illustrated in Figure 3. The function block specification is as precise as any program code.

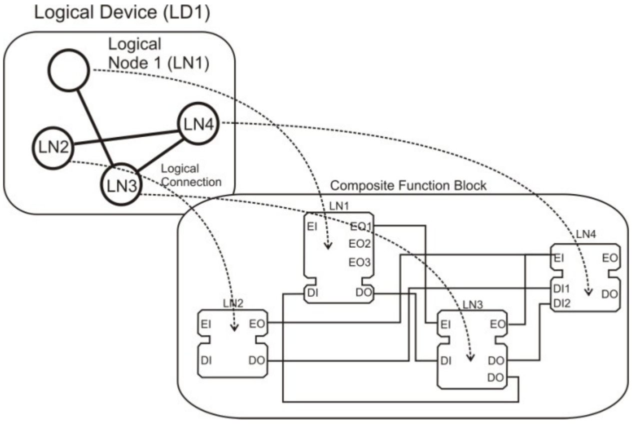


Figure 3. Conceptual idea of implementing IEC 61850 Logical Nodes and Logical Devices using IEC 61499 basic and composite function blocks.

Most Logical Nodes of IEC 61850-7-4, IEC 6150-7-410, or IEC 61400-25 can be modelled as function blocks. The logical node concept can be mapped to the function block concept as shown in Figure 4.

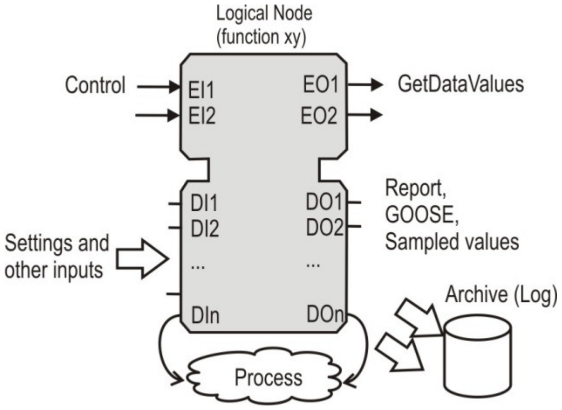


Figure 4. Conceptual representation of a Logical Node modelled as a function block.

Any data object shown as output data of the “function block” can be communicated by the communication services of IEC 61850-7-2:

- GetDataValues (read or polling)
- Report values immediately (event driven, sequence of events)
- Log values and query log at any time
- Send values peer-to-peer by multicast mechanisms (typically *Generic Object Oriented Substation Event – GOOSE* for status information and *Sampled Values – SV* for samples of voltage, current or vibration).

The data objects *EnaOpn* and *EnaCls* of the Logical Node *CILO* (interlocking) could be understood as output data of a function block instance. The input data representing the switch gear positions would (in the IEC 61850 context) would be modelled with SCL as the input section of the Logical Node *CILO*. The configuration or control values would be modelled as data objects.

These communication services are mapped onto MMS (ISO 9506, Manufacturing Message Specification) in IEC 61850-8-1. A new standard (IEC 61400-25-4 – extensions of IEC 61850 for wind turbines) provides also web services that implement the abstract services of ACSI (IEC 61850-7-2, Abstract Communication Service Interface).

Any microprocessor device compatible with IEC 61499 will be able to execute this specification directly and with the same result. Thus, the virtual substation function can be implemented as a function block application and can be simulated. After the functionality is validated by simulation, the same function blocks can be directly deployed in particular physical devices.

The function block implementation specifies logical connections between the logical nodes in detail, implementing them via event and data connection arcs.

The benefit of IEC 61499 compliance can be seen by comparing the general purpose microcontroller device (MCD) in Figure 5 with the IEC 61499 compliant one in Figure 6. To create an application specific device, say a bay control unit or an intelligent circuit breaker, based on a MCD with appropriate peripherals (e.g. input/out ports, communication interfaces, etc.) one needs to program its various functions in some programming language, perhaps using library functions provided by an application programming interface. The latter may be needed to access the peripherals (e.g. write value to an output port). Then, using a device-specific compiler, the executable code can be generated and uploaded to the device’s memory using the services of its embedded operating system.

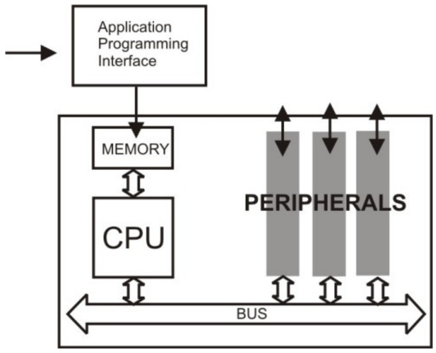


Figure 5. General purpose microcontroller-based control device.

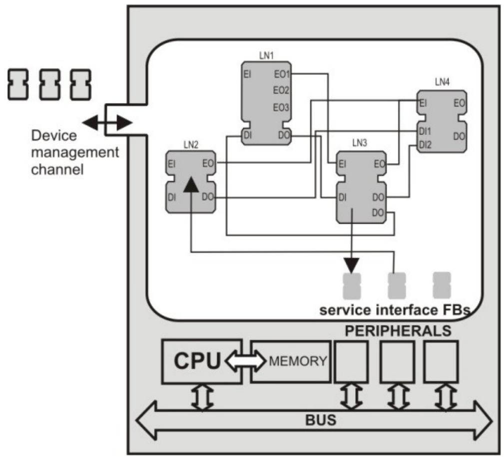


Figure 6. IEC 61499 – compliant device.

The IEC 61499 compliant device masks all the hardware and software (e.g. OS) details, offering a concept similar to a virtual machine, in which function block applications are executed. An application is a collection of *function block instances*, obtained from the library of *function block types,* and connected via event and data connection arcs. The peripherals are accessed by instantiating and using *Service Interface Function Blocks*.

The IEC 61499 compliant device provides a mechanism for managing its status and functionality. There is a “device management channel”, through which a configuration tool can change the application inside the device, or its FB libraries, or its operation mode (e.g. to start and stop execution of the application, etc.). The protocol is open and is a part of the IEC 61499 standard. Thus, there is a lot more re-use potential for the application than in the general purpose MCD.

These benefits become even more apparent when a distributed application is considered, as shown in Figure 7. Here, the application consisting of function blocks is intended to be executed on two network-connected devices. Compliance of both devices with IEC 61499 will guarantee that execution results will be exactly the same as if the FB application was running all in one device. Prior to distribution the application can be tested on one machine, then the blocks can be mapped to hardware as desired, adding some communication FBs (send – receive) in places where event and data connections intersect the device boundaries.

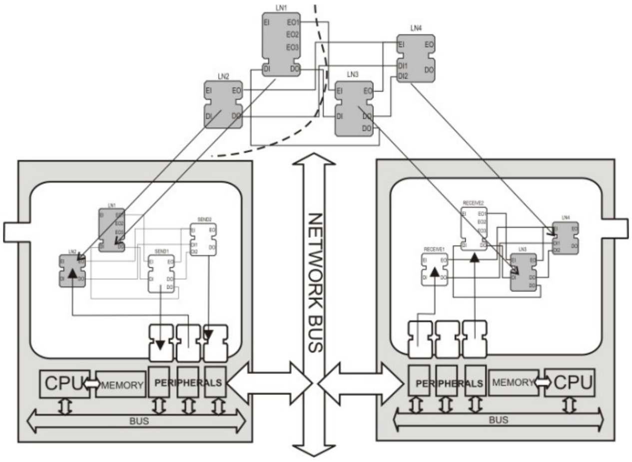


Figure 7. Compliance with IEC 61499 simplifies development and implementation of distributed applications.

Thus, domain-specific control devices can be built ‘on top’ of IEC 61499 compliant devices just by adding specific FB libraries, thus creating an extra layer (or layers) specific to the particular application domain. This is illustrated in Figure 8. A similar approach was explored in [6] for creating the open computer numeric controller (CNC).

The high-level communication protocols specified by IEC 61850 (e.g. GOOSE) can be implemented in communication FB libraries. One can envisage communication function blocks for GOOSE, SV, Control, Reporting, Logging, etc.

C. *Benefits of IEC 61499 compliance*

This architecture can be appreciated not only by the established vendors of such domain-specific controllers, but also by independent software vendors, that can develop such virtual power-control devices as libraries of function blocks and then easily port them into a multitude of IEC 61499- and IEC 61850-compliant devices.

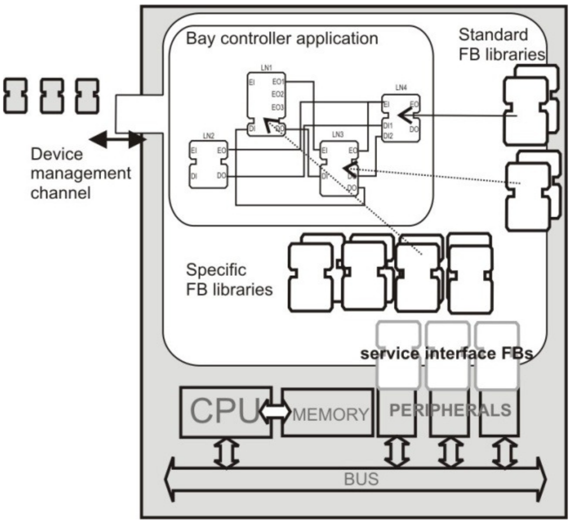


Figure 8. Domain-specific controller obtained from the IEC 61499-compliant controller by adding specific libraries of function blocks.

System integrators will get controllers whose internal structure is customisable for particular projects. Validation of the control and automation functions will be possible by simulation of the corresponding function block applications, taking into account the structure and logic of the whole substation.

End-users will be able to modify the firmware of their substation controllers during their lifetime. They will be able to develop substations with more intelligent behaviour, capable of adapting to the changing grid configuration or state. The combined 61850/61499 architecture will help end-users to better manage intellectual property and even sell it to the third-party companies.

D. *Embedded implementations of IEC 61499*

At the level of fault detection algorithms, protection systems are essentially sampled data systems, with sampling typically occurring 80 times per 50/60Hz cycle. This processing rate may seem to be challenging for IEC 61499 implementations.

The first trial IEC 61499 implementations, e.g. FBRT [7] and FUBER [8], were Java-based and not up to such real-time performance requirements. However, subsequent implementations, also Java based, such as [9] and RTSJ-AXE [10], or non-Java based, such as FORTE [11], have demonstrated sufficient performance to implement, say, inverted pendulum control. Even higher performance can be expected from the FB – Esterel implementation reported in [12, 13], which can be implemented in pure hardware.

The first commercial implementation of IEC 61499 by ISaGRAF v.5.0 also is comparable in speed with scan-based programmable logic controllers (PLC).

This progress in IEC 61499 implementations provides assurance that IEC 61499 compliant devices will ultimately have sufficient performance to implement any power system automation function, but in the first instance function blocks can be used to represent protection functions as black boxes embedded in complex automation systems.

E. Communications

IEC 61499-compliant devices need to have extensive networking capabilities to be used in the role of the domain-specific controllers. As previously mentioned, SCADA communications networks have traditionally been designed to support centralised monitoring and control. Many utilities are in the process of rolling out optical fibre – at least to their zone substations and sometimes beyond – and replacing antiquated serial links with IP-based communications. These new networks typically have high-availability architectures and provide different grades of service according to application requirements. An advantage of IP is inherent support for peer-to-peer communications (assuming that the application-level protocols can take advantage of this).

Communications with geographically dispersed feeder equipment are typically radio-based and non-IP. For example, ENERGEX has just begun to roll out a "mesh radio" network for distribution SCADA. This network supports peer-to-peer communications, and provides a measure of redundancy, although it will initially be used for traditional SCADA.

V. INTERPLAY BETWEEN IEC 61850 AND IEC 61499

A. Relationships between IEC 61850 and IEC 61499 for automation functions

The term *automation function* is used to differentiate the functions and communication for controlling (involving automatic functions like tripping a circuit breaker, preventing an operation due to a specific interlock condition, or restoring supply to blacked out customers) and those for monitoring from a supervisory point of view (e.g. a SCADA system keeping track of sequence of events). The use of IEC 61850 models and its relationship with IEC 61499 for control functions is illustrated in Figure 9.

Case a) in Figure 9 shows a single device that implements the control function of a unit of switchgear (circuit breaker, load break switch, disconnector, etc.). The control function is represented in IEC 61850 as a Logical Node with the name *CSWI*. The CSWI has a data object *Pos* with the attribute *ctlVal* (control value) that can be addressed by a substation computer. The substation computer sends a control message to the device with the Logical Node *CSWI* – it addresses the attribute *CSWI.ctlVal* and sets it to Open or Close.

The operation to close a circuit breaker will not be allowed if the configured conditions for blocking the open or close are fulfilled. For example, if an adjacent earthing switch is in the closed position, closing a circuit breaker would cause a short circuit and would probably damage the primary equipment.

The function which checks whether the conditions are met is modelled in IEC 61850 with the Logical Node *CILO* (control interlocking condition). This interlocking function is well known in substations. The CSWI has to communicate with the CILO to figure out what is allowed.

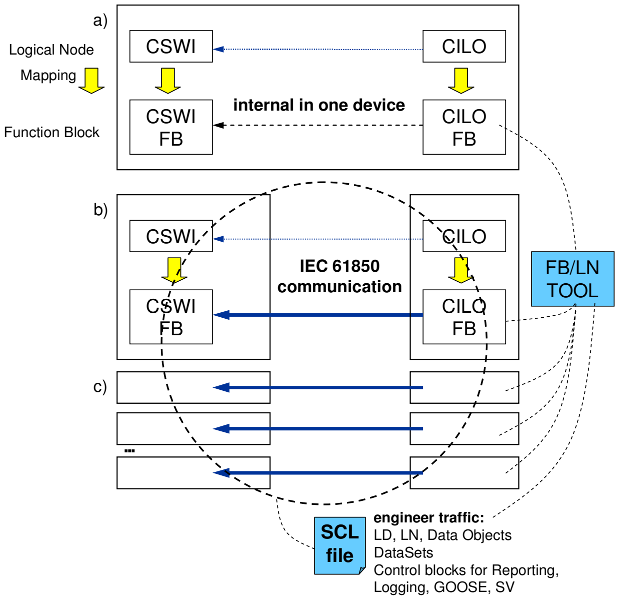


Figure 9. The use of IEC 61850 models and its relation to IEC 61499 for control functions.

The functionality described above may be implemented by any means – IEC 61850 does not standardise the implementation. Since we discuss the use of IEC 61499 we can easily map the functionality of Interlocking to two function blocks – CSWI and CILO. The function blocks would have programmed logic describing how the blocking conditions for opening and closing allowed are calculated. This requires also the specification of the "input signals" (mainly the switch positions of related switches). These input signals are specified in SCL.

In case b) two logical nodes CSWI and CILO are implemented in separate devices – this requires communication using IEC GetDataValues, Reporting or GOOSE. In case c) several devices need to exchange information for their functions.

The mapping from IEC 61850 based Logical Nodes and data objects to function blocks is required if the design of a substation is mainly done by a tool that implements SCL. But the design can also be done with a tool that uses the IEC 61499 function block models. In the latter case the function blocks would hide the Logical Nodes. The SCL file for the interlocking function (CSWI and CILO) would automatically be generated by the function block specification tool.

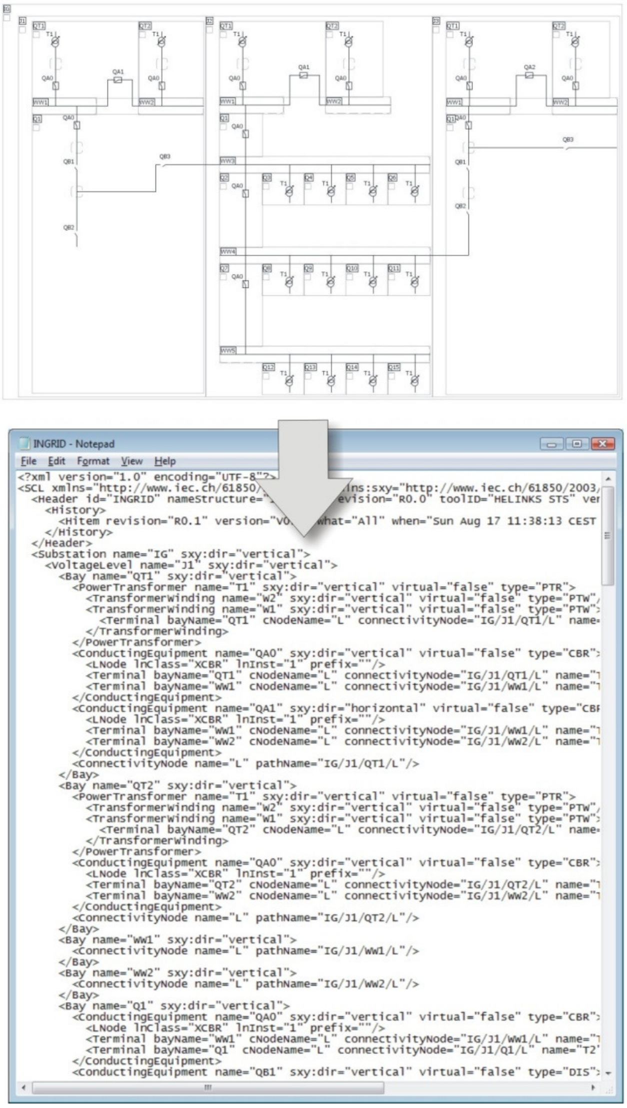
The specification of the function can principally be done by a tool that uses the Logical Node view (generating the corresponding SCL file), or by a tool that applies the function block view. Which one is the preferred solution depends on many issues.

Case c) depicts a situation where the tools (either LN or FB centred) have built-in mechanisms to map the specified functions to function blocks and a SCL file. The SCL file may be used to configure a SCADA system to receive the sequence-of-events of the switch operations. Each time the switch position (*CSWI.stVal* – status value) changes the device would send a report message with the new state indication (usually with time stamp and quality information).

The SCL file may also be used to document the communication with regard to Logical Nodes, data objects, data sets, and control blocks.

Software tools can automatically generate the corresponding function block applications given the appropriate FB libraries. The first step will be to draw the single line diagram with functions like *CSWI* and *CILO* assigned to the primary equipment, and convert this information (representing functions) to the SCL document as illustrated in Figure 10 for our sample power distribution utility. Then the SCL will be used as the source for creating the FB application. IEC 61499 tools will be able to deploy it to a network of distributed control devices.

The communications would preferably be based on the abstract services defined in IEC 61850-7-2 and implemented according to IEC 61850-8-1 with MMS (ISO 9506) or IEC 61400-25-4 (web services).



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<?xml version="1.0" encoding="UTF-8"?>
<SCL xmlns="http://www.iec.ch/61850/                 lns:sxy="http://www.iec.ch/61850/2003/
  <Header id="INGRID" nameStructure="               evision="R0.0" toolID="HELINKS STS" ver
    <History>
      <Hitem revision="R0.1" version="V0.      what="All" when="Sun Aug 17 11:38:13 CEST
    </History>
  </Header>
  <Substation name="IG" sxy:dir="vertical">
    <VoltageLevel name="J1" sxy:dir="vertical">
      <Bay name="QT1" sxy:dir="vertical">
        <PowerTransformer name="T1" sxy:dir="vertical" virtual="false" type="PTR">
          <TransformerWinding name="W2" sxy:dir="vertical" virtual="false" type="PTW"
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            <Terminal bayName="QT1" cNodeName="L" connectivityNode="IG/J1/QT1/L" name
          </TransformerWinding>
        </PowerTransformer>
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        <ConnectivityNode name="L" pathName="IG/J1/QT1/L"/>
      </Bay>
      <Bay name="QT2" sxy:dir="vertical">
        <PowerTransformer name="T1" sxy:dir="vertical" virtual="false" type="PTR">
          <TransformerWinding name="W2" sxy:dir="vertical" virtual="false" type="PTW"
          <TransformerWinding name="W1" sxy:dir="vertical" virtual="false" type="PTW"
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      </Bay>
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      </Bay>
      <Bay name="WW2" sxy:dir="vertical">
        <ConnectivityNode name="L" pathName="IG/J1/WW2/L"/>
      </Bay>
      <Bay name="Q1" sxy:dir="vertical">
        <ConductingEquipment name="QA0" sxy:dir="vertical" virtual="false" type="CBR"
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        </ConductingEquipment>
        <ConductingEquipment name="QB1" sxy:dir="vertical" virtual="false" type="DIS"
```

Figure 10. Single line diagram for the sample system and the generated SCL document.

B. Relationship between IEC 61850 and IEC 61499 for monitoring functions

Generic monitoring functions are well defined in IEC 61850-7-2 (Polling, Monitoring, Reporting and Logging). The function block view for monitoring could easily be mapped to IEC 61850 communication services. Conversely, the IEC 61850 generic monitoring functions and services could easily be modelled as standard function blocks according to IEC 61499.

The configuration of reporting and logging as well as the limits of analogue values to be monitored (low-low-limit, low-limit, high-limit, high-high limit, etc.) could be done by an input signal in a function block view and mapped to data objects of the corresponding Logical Nodes (see Figure 11).

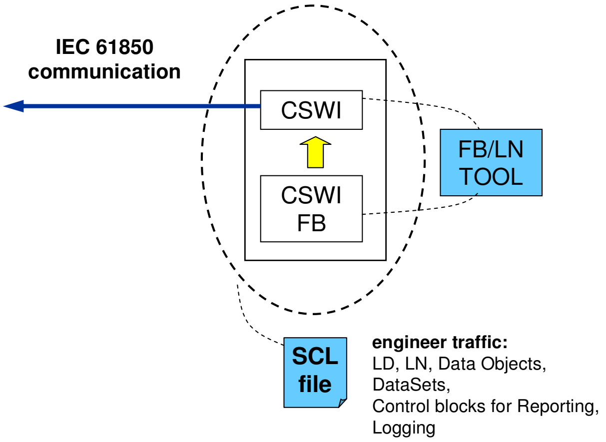

Figure 11. The use of IEC 61850 models and its relation to IEC 61499 for monitoring functions.

The communication of the status indication of the *CSWI.Pos* could use the services for event-driven reporting as defined in IEC 61850-7-2.

The information model of the device (in this case the *CSWI.Pos.ctlVal* and *CSWI.Pos.stVal*) and the needed communication are specified in the corresponding SCL file. A server according to IEC 61850-7-2 could automatically read the SCL file, configure a server and generate the corresponding simulation application (in terms of IEC 61499 function blocks). The simulation of power system measurements could be done with different precision levels – from discrete sets of values to more realistic continuous change. The simulation could be conducted on the same computer as the IEC 61850 server.

VI. SCENARIO FOR DISTRIBUTED FAULT LOCATION, ISOLATION AND SUPPLY RESTORATION

The need for more flexible and intelligent control of power distribution systems will be illustrated on example system of Figure 12, which shows three 11kV feeders supplied by three different zone substations. They could be supplied by the same zone substation – this aspect is not important. The 11kV feeders are shown in simplified form, with only the backbone and ties to adjacent feeders. In reality, 11kV feeders have a branching structure such that the feeder and the associated LV feeders can supply a geographical patch[1].

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[1] For example, in ENERGEX the average topological profile of urban 11kV feeders is backbone plus three second-level spurs plus one third level spur (1/3/1). The average topological profile of ENERGEX's rural 11kV feeders is (1/9/6/1).

Distribution substations are positioned along each feeder as required to serve customers' loads.

In the initial state the switches ROS3, ROS4 and ROS 9 are open, which is denoted by their white colour respectively. All other switches are closed, denoted by their dark colour. The switches are assumed to be "smart" and participating on an ongoing event-driven conversation.

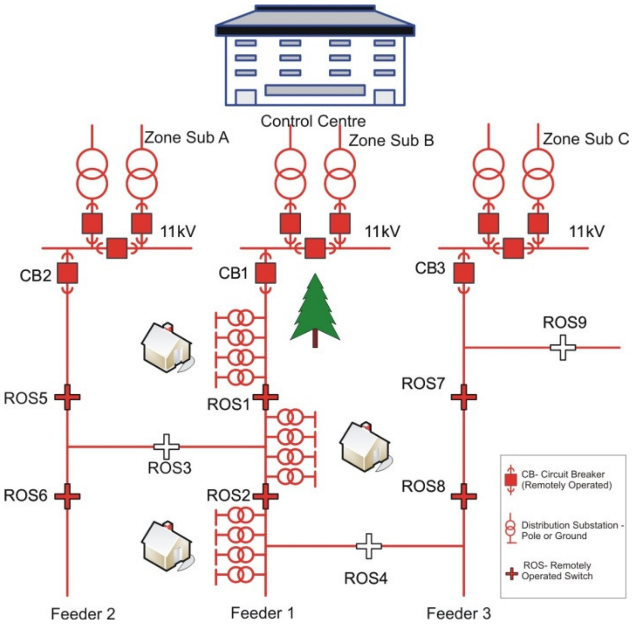


Figure 12. Sample power distribution utility with intelligent distributed control.

The scenario begins with a tree falling on the 11kV mains, causing a permanent fault on feeder F1. The feeder protection *trips* (opens) circuit breaker CB1 at zone substation B. Sectionalising switches ROS1 and ROS2, being downstream of the fault location, do not register the passage of fault current. In anticipation of possible follow-up action, they remember the load currents that were flowing through them just before the fault occurred. After one attempted automatic reclosure, CB1 goes to lockout.

Tie switches ROS3 and ROS4 realise that feeder F1 is no longer energized, and they initiate a search for alternative sources of supply. Each switch is assumed to maintain a local connectivity map, so it is able to propagate the "call or help" towards a zone substation. CB2 at zone substation A, and CB3 at zone substation C, respond with information about the headroom (excess capacity) available. This information propagates back down feeders F2 and F3. It is updated at each switch so that, by the time it reaches ROS3 and ROS4, the available excess capacities can be compared with the loads in the unfaulted sections of feeder F1 (note that in order to achieve this, each switch must be aware of its own rating and the ratings of the downstream conductors).

The switches agree on the steps necessary to restore supply: The mid-section of feeder F1 will transferred to feeder F2; the tail-section will be transferred to feeder F3; the head-section will have to await repair.

In the meantime, the control centre has been eavesdropping on the conversation between the switches. When customers call to report a loss of supply, each can be fully informed as to when they can expect restoration. In fact, customers on the unfaulted feeder sections will probably be restored before they have time to call.

Having restored supply to as many customers as possible, the switches go quiet. A repair crew is dispatched to patrol the faulted feeder section, find the fault and repair it. On completion of the repairs, the switches are commanded to restore the distribution system to its pre-fault configuration.

This particular scenario is one of the simplest possible. It does not account for load increase and decrease over the daily load cycle, dynamic ratings of equipment, the possible need for second order load transfers to free capacity on the immediately adjacent feeders, the need to ensure that the system remains protected at all times, the need to manage embedded generation, and a host of other possible complications. Nevertheless, it demonstrates that, at least in one situation, it is possible for collaborating distributed components to solve a problem without central intervention.

VII. INTELLIGENT CONTROL AND SIMULATION WITH FUNCTION BLOCKS

A. Feeder model

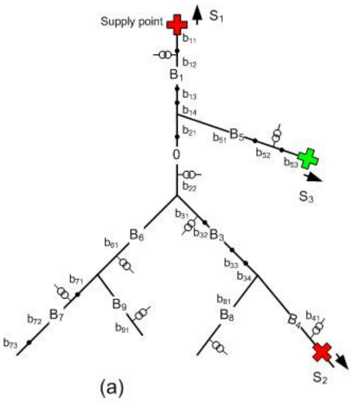
As previously mentioned, 11kV feeders typically have a branching topology, with distribution substations positioned as required to serve customers' load. The dominant influence on feeder topology is the evolution of customer's load over time, and each feeder has a unique topology. Differences between construction standards at different times in the life of a feeder can lead to significant non-uniformity in terms of ratings.

For the purposes of this exercise, it should be assumed that useful power system measurements can be only be made at switch locations, i.e. at the locations of circuit breakers, sectionalising switches and tie switches.

In future, distribution substation and/or customer meters will be remotely monitored and controlled. Current thinking is that the associated data will be communicated on a separate network from the SCADA data communications network, and not in real-time, however the argument is made below that a real-time subset of the meter data should be made available to the automation system.

Whereas switches with embedded controllers are becoming quite common, wires and cables are as "dumb" as anything can be, and are likely to remain so. As a result, it will not be possible for switches to communicate with the associated connectivity in order to discover the topology and ratings of the feeder. They will have to be given this information by a higher authority. The authority which supplies switches with topology and ratings data will (potentially) be able supply complex historical data about loads, enabling inferences (not always completely accurate) to be made in real time.

Figure 13 summarises this situation. Figure 13(a) shows the detailed topology of a feeder section. Figure 13(b) shows the corresponding "reduced" topology, together with the conclusions that can be safely made in real-time using data given to, and exchanged between, the switches.



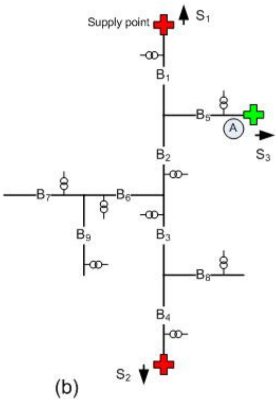


Figure 13. Feeder section topology.

The notation used in the Figure is as follows:

B_i - Feeder branch (i = 1..N);
b_{ij} - Wire or cable forming part of feeder branch B_i;
r_{ij} - Rating of wire or cable b_{ij};
R_i - Rating of branch $B_i = min_j(r_{ij})$;
$L_i = P_i+jQ_i$ - Net load on branch B_i;
$L = \sum Li$ - Total load on feeder section;
$S_k = P_k+jQ_k$ - Power flow out of switch k (k = 1..M)
C_1 - Headroom (excess capacity) available at supply point;
C_k - Headroom available at (open) switch k;

In the absence of direct load measurements, L can be calculated as $L = -\sum S_k$.

Ignoring ratings

$$\left|C_k\right| < \left|C_1 - \sum_{k=2..M} S_k - L\right| < \left|C_1 + S_1\right| \qquad (1)$$

(noting that $S_k = 0$ because switch k is open)

If there is no embedded generation, and if all loads are in the same quadrant (e.g. all with lagging power factor), wire and cable ratings can be taken into account conservatively as follows:

Assume L is located at point A near switch k. Then

$$\left|C_k\right| < \min_{i=1..k}(R_i - L) \qquad (2)$$

where 1..k signifies the path from switch 1 to switch k.

$\left|C_k\right|$ will be the lower of the two estimates from (1) and (2).

The effect of embedded generation and/or leading power factor will generally be to improve headroom (by partially compensating the load inside the feeder section). However the occurrence of high loads within the feeder section will not be precluded (e.g. between a large embedded generator and a large customer, both on the path from switch 1 to switch k). Under these circumstances it will not be possible to make a conservative estimate using only measurements at the boundary of the feeder section.

Also, if there is a large amount of embedded generation (approaching a net export from the feeder section), this simple "algebraic" form of calculation is unlikely to yield accurate results.

These problems can be overcome if real-time load measurements from distribution substations can be combined with the switch measurements and topology data. Then it will be possible to estimate the load flow within each feeder section with reasonable accuracy for load in all quadrants. Doing so will require a shift from a "stovepipe" architecture (in which meter data is reserved for metering-related functions and SCADA data is reserved for SCADA-related functions) to a more holistic architecture.

B. Distributed simulation and control with function blocks

The idea of function block modelling of the sample system is presented in Figure 14. Here each element of the distribution system is modelled by one function block. To support this, a library of basic function block types must be developed: CB (circuit breaker), ROS (remotely Operated Switch), etc.

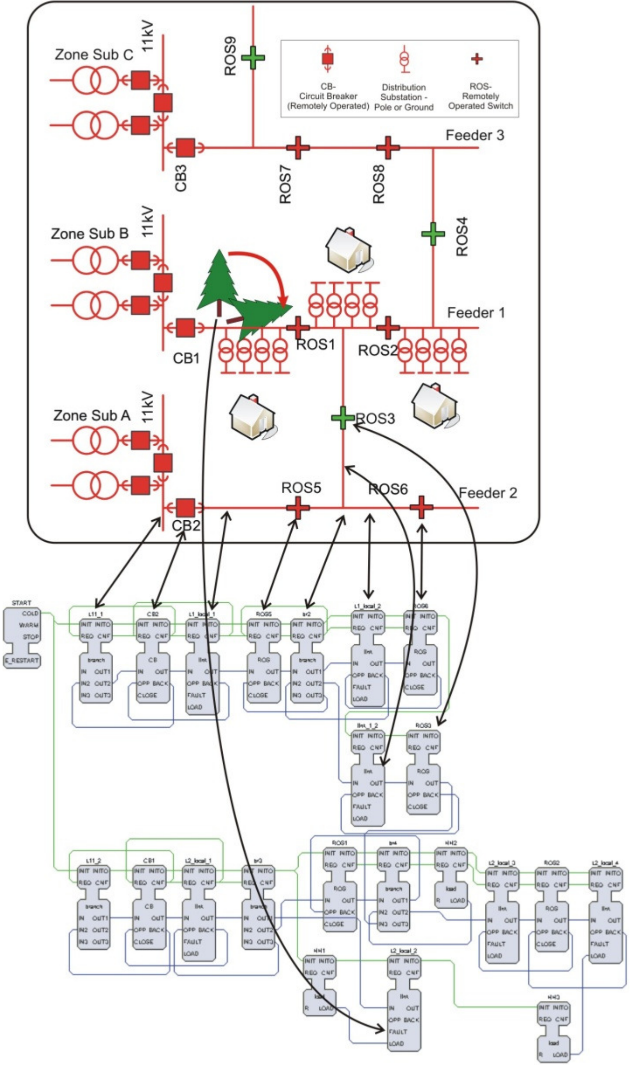


Figure 14. Function block application for distributed simulation and control of the sample system.

The idea of distributed control is similar to the one proposed in [14] for airport baggage handling systems, built using conveyor grids. Each piece of physical equipment is represented by a function block in the FB diagram. These blocks are internally organized following the Model-View-Control design pattern [15]. Some, like the Circuit Breaker (CB) encapsulate its own controller along with model and view, others, corresponding to dumb equipment like sections of wires, are represented only by model and view. As a result, the function block application simulates the depicted distribution system and implements its decentralized control.

The modelling of rating values is based on the analytic estimations (1) and (2) in the previous subsection.

Each function block has input FAULT reserved for modelling fault-causing events in the particular section modelled by that block. Thus, the tree fall is modelled by setting the FAULT input of the FB "L2_local_2" modelling the corresponding section of wires (FB type "link").

VIII. CONCLUSION AND FUTURE WORK

In this paper we discussed a pathway to flexible power system automation. This involves the use of IEC 61499 as an integration, extension and verification mechanism for IEC 61850-based systems. A fault location, isolation and supply restoration scenario was presented, and its implementation using IEC 61499 function blocks was sketched.

In order to enhance the benefits of this approach, devices like protective relays, bay controllers and substation controllers could be implemented on IEC 61499-compliant platforms, which would add new value to IEC 61850 compliance – the ability to customise protection, monitoring, control and automation functions. IEC 61499 could also be extended also towards power system equipment – circuit breakers, transformers, merging units, etc. The required performance is within the reach of powerful embedded computing platforms.

The realisation of this vision depends on the creation of a ubiquitous peer-to-peer communications network of adequate speed, resilience and security. While this is certainly within the capabilities of current technology, the Industry standards necessary for universal interoperability and cost reduction are very early works in progress.

Our future work will follow three main directions:

(1) We will build the complete FB library for creating automation systems based on collaborating distributed components and libraries for monitoring functions. Such libraries may include "standard" function blocks, for example for the logical nodes described in IEC 61850-7-410 or for communication services like reporting and logging. We will also investigate the most appropriate forms for representing the reasoning logic of autonomous intelligent controllers. The IEC 61850 Substation Configuration Language (SCL) can be used as the system description specifying all information generated and consumed and the methods on how and when to exchange values produced by the functions, so the required logic should automatically be mapped to IEC 61499 function blocks that represent communication with IEC 61850-7-2 service models.

(2) We plan to investigate the requirements and feasibility of creating the range of control devices on top of IEC 61499 embedded computing platforms, mimicking and extending existing IEC 61850-compliant devices (1).

(3) We plan to investigate the requirements and feasibility of "plug-and-play" self re-configuration the power system - the ability to automatically detect changes in the fabric of the power system, and re-configure protection and automation systems appropriately.

IEC 61850 lacks the specification of functions, and IEC 61499 lacks "standard" communication services. The best features of each standard can satisfy the needs of the other, creating an architecture for truly flexible and adaptable power system automation.

IX. ACKNOWLEDGEMENTS

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