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Multi-agent Smart Grid Automation Architecture based on IEC 61850/61499 Intelligent Logical Nodes

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Abstract— **Universal, intelligent and multifunctional devices controlling power distribution and measurement will become the enabling technology of the Smart Grid ICT. In this paper we report on a novel automation architecture which supports distributed multi-agent intelligence, interoperability and configurability, and enables efficient simulation of distributed automation systems. The solution is based on the combination of IEC 61850 object-based modeling and interoperable communication with IEC 61499 function blocks executable specification. Using the developed simulation environment we demonstrate the possibility of multi-agent control to achieve self-healing grid through collaborative fault location and power restoration.**

Index Terms-- **Smart Grid, multi-agent control, simulation, IEC 61850, interoperability, distributed intelligent automation, IEC 61499, feeder automation, self-healing.**

I. Introduction

The automation of power distribution systems is designed according to two contradictory design goals. On the one hand, power distribution systems have to be robust to avoid power outages even in presence of serious external disturbances, such as natural disasters, equipment failures or demand/supply fluctuations. Achieving this goal requires redundant hardware and sophisticated control algorithms. On the other hand, such systems have to be economically viable, and, moreover, providing for efficient power consumption in accordance with the latest "green society" trends. This goal asks for less redundancy but more flexibility, adaptability and re-use of solutions.

Achieving the synergy of these design metrics is the goal of many Smart Grid R&D projects. A revolutionary Information Communication Technologies (ICT) infrastructure is required to achieve robustness, adaptability, self–healing and self–protective capabilities to support highly dynamic networks of power producers and consumers (*prosumers*). As pointed out in the strategic roadmap [1], the advanced ICT will incorporate into the grid "the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand at the device level".

Designing such ICT is a major challenge due to the complexity of the control which, in general, cannot be tackled by the traditional hierarchical control design approaches. The future Smart Grid ICT will be more like an artificial nervous system where many tasks are accomplished by horizontal collaboration of neighbouring autonomous control agents, rather than involving the entire system hierarchy. The multi-agent control concepts, e.g. [2], are being investigated to fulfil the seemingly un-combinable requirements of increased reliability, economic feasibility and efficiency. However, multi-agent control has been mostly experimented in research labs with a huge gap to the commercial hardware/software design practices.

In this paper we propose a pathway for industrial deployment of such multi-agent ICT architectures. The proposed approach is inspired by the use of multi-agent systems in other automation applications, such as manufacturing [3, 4] and power electronics [5].

A "collateral benefit" of using multi-agent control in Smart Grid ICT is flexibility of accommodating different functions and combining them in various combinations dependent on the state of the environment, internal state and other inputs. One should also note that during the system's lifetime the set of ICT functions may require upgrades. The flexibility, however, is imposing a new challenge: verification and validation of such control systems. The simulation approach is not easy to apply due to the complexity of systems' modelling. When control components come from different vendors, it is a major effort to even integrate them into a single system. When it comes to modelling, the overhead of designing a model is comparable to the system development from scratch.

This paper proposes a solution that attempts to solve both mentioned problems at once. The proposed novel automation system architecture is based on the concept of Intelligent Logical Nodes (ILN), which is an extension of the familiar logical node concept used in substation automation; but enhanced with intelligence to act independently at the local level and within the team (the whole system) by collaborating with peers (other ILNs). The roadmap [1] emphasized the importance of standardisation, therefore the proposed architecture is based on two open standards:

- The executable specification in form of function blocks of IEC 61499 [6] is used to encapsulate and implement the intelligent control agents. In this form, the agent solutions can be easier validated and immediately deployed to networked embedded control devices.
- The agents are structured according to and communicate via the services of IEC 61850 [7] – the international standard proposing an open communication and object-oriented data model for intelligent control devices in substation automation.

The IEC 61499 function blocks architecture is a convenient abstraction for modeling distributed multi-agent control system following the multi-layered architecture of IEC 61850. On the other hand, this solution shows a direct pathway to deployment of multi-agent controls on networked embedded control devices, which will pave the way to the industrial adoption of the automation and monitoring devices capable of combining different functions and achieving goals in collaborative effort with other such devices. Prior to the deployment, the behaviour of such complex systems can be verified through simulation.

To illustrate the intelligent behaviour, we use an automated fault location, isolation and service restoration (FLISR) scenario. The demonstration shows how the so-called “self-healing grid” can be achieved by collaboration of intelligent logical nodes without any central controller. This result has been confirmed in the developed simulation environment. The proposed architecture, however, is not limited to intelligent fault management only and can accommodate and combine other Smart Grid functionalities.

The rest of this paper is structured as follows. Section II briefly reviews the state of the art of Smart Grid automation. The objective of this work and summary of the contribution is formulated in Section III. Section IV presents the core idea of the proposed device level automation, which is based on the harmonisation of two international standards IEC 61850 and IEC 61499. The section describes the developed architecture of an intelligent logical node. Section V presents a scenario used in this paper as a running reference example. Section VI suggests a hierarchical architecture of the multi-agent system and elaborates on distribution of control functions among different layers of control system and types of control nodes. Based on this architecture, in Section VII we present a model of a power system utility with distributed control implemented. Section VIII discusses the negotiation tactics taken by intelligent logical nodes of the developed system to achieve automated FLISR. Section IX presents the simulation environment where distributed control approach was tested. The paper is concluded with a summary and ideas for future work.

II. State of the Art and Advanced Research

A. Smart grid vision and IEC 61850 standard for substation automation

According to [8], Smart Grid will emerge as an integration of electricity and communications, so that electric network will be “always available, live, interactive, interconnected and tightly coupled with the communications in a complex energy and information real-time network”. The result will be more efficient power systems better managing the growing power consumption, providing fault resilience and seamlessly integrating distributed renewable sources, such as wind and solar.

One of the many challenges in achieving this is intelligent management of Smart Grid components, such as distributed generation (DG), batteries, loads and new generation solid state transformers. To integrate the heterogeneous DG components, producing different types of electricity (dc, ac) at different voltage levels with different power capacity [9, 10], the future grid requires reliable, fast and cost-effective communication (media, protocols and security), and new generation of embedded control devices [10-12].

The new IEC 61850 standard - Communication Networks and Systems in Substation [13], addresses the interfacing issues and standardizes communication to avoid the use of vendor specific protocols. Thus it creates the potential for future automation and control functions and enables power systems to advance into SmartGrid [14-18].

B. Power system automation architectures

According to [19], advanced state of the art systems tend towards the architecture presented in Figure 1 (top side). There are three basic components: objects, network and control centre. The object component comprises intelligent electronic devices (IEDs), microprocessor-based relays, remote terminal units (RTUs) and Programmable Logic Controllers. They perform local control, send and receive signals to/from other peers or Supervisory Control and Data Acquisition (SCADA) master. The component consists of two levels: primary equipment and bay level (local intelligence in the form of IEDs and RTU). The communication network interfaces the bay level functions with the SCADA station level control. The SCADA master implements central control functions: information processing and decision making, information display for SCADA operator, and control of the power system through the bay level devices.

The research is being carried out towards the advanced substation automation proposing such technologies as multi-agent systems [2], advanced coordination [20], dynamic topology engine [21], waveform analysis [22] and the method of island operation [23]. It is envisaged in the majority of these works, that future substation automation systems will be more relying on the horizontal communication between IEDs as represented in Figure 1 (bottom side).

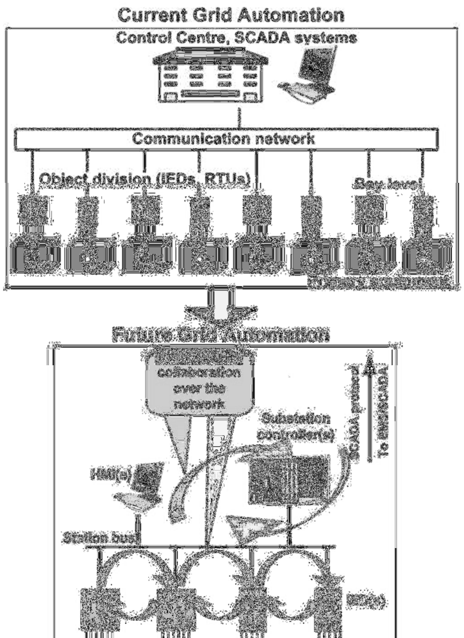

Figure 1. The shift from traditional architecture with central control towards Smart Grid with decentralized decision making.

C. Fault location, isolation and supply restoration

One of the landmark features of the Smart Grid concept is the idea of automated FLISR, the so called “self-healing” grid. In many current systems, the FLISR procedure is not fully automated, but facilitated using advanced technologies that can reduce the outage duration and improve the repair team efficiency. In more advanced systems the FLISR function automatically senses the faults (e.g. in feeder circuit breakers and downstream re-closers), identifies the fault section, isolates the fault and restores power to customers by automatically switching them to a non-faulted section of the system. This minimizes the workload for the field crews, provides almost immediate power restoration for the consumers, and improves reliability and robustness of the distribution network. Moreover, wireless sensor network is proposed to be a crucial part of self-healing Smart Grid, reacting to online events in real-time [12] and maintaining high reliability. The demand for power system reliability is increasing, which leads to greater demand in the market for "smart" restoration solutions. A few utilities have reported centralized systems for advanced FLISR, for example [24].

D. *Multi-agent approach to grid automation*

The main drawback of the central control FLISR solution is insufficient response time due to the geographical distribution of the primary equipment across the deployment areas. The multi-agent approach to power system restoration promises to overcome this fundamental limitation. The main concept of multi-agent based system is the distribution of control functions and decision making authority locally in the responsibility area where the agents operate.

For example, Nagata and Sasaki in [25] propose a remarkable multi-agent system where the agents exhibit collaborative behavior to implement FLISR. Their proposed system has a number of bus agents (BAGs) and a single facilitator agent (FAG). The BAG has a goal of finding suboptimal target configuration after a fault has occurred by cooperation with other peers (BAGs). The authority to make the decision is given to FAG which is acting as a manager. Similar multi-agent approaches have been investigated by several other research groups, for example: IntelliGrid Consortium [26], Virginia Tech [2] and Li *et al* [27].

III. This Work's Motivations and Contributions

This paper is motivated by the need and possibility of using intelligent ICT based on multi-agent control at the device level of Smart Grid. This possibility was foreseen by power system research community and mentioned in [10] which has indicated two different levels of intelligence in future grid: "one to manage the energy process and one to manage fault conditions". However, the hardware/software platforms currently used in automation do not support properly the available multi-agent technologies. In the traditional automation architectures, the complicated algorithms of the multi-agent control cannot deliver sufficient real-time performance and determinism even on the top-end hardware. Thus, practical usage of the intelligent multi-agent technology in power system control and operation requires next generation of IED. One requirement to such IEDs is to have open architecture based on standards in the areas of communication and distributed automation [28].

This paper contributes to the achievement of this goal as follows:

- The novel architecture of distribution systems automation is proposed, which facilitates the use of fully distributed multi-agent control in power distribution automation. The architecture links two reference architectures of IEC 61850 and IEC 61499, making the static structures of IEC 61850 executable and intelligent;
- Within the architecture we propose a hierarchical arrangement of logical nodes' types into a layered hierarchical architecture. This is based on the analysis of their functions and reveals the potential of optimizing their complexity and data flows on account of re-using functions.
- The developed architecture specifies a design template for executable ILN, the basic building blocks of the automation functionality. It also demonstrates how distributed control components (IEDs) can be composed of communicating ILNs.
- The way to encapsulate the algorithms of intelligent behaviour into ILNs has been demonstrated and the behaviour has been validated on a FLISR example.
- The feasibility of the proposed approach has been proven by simulation. For that, a co-simulation testbed has been created that is composed of Matlab Simulink (for the model of the plant) and Function block execution environment (for the model of controller).

IV. Device Level Distributed Automation

A. *IEC 61850 and IEC 61499 and their harmonisation*

In this paper we are implementing the standards' harmonization approach whose idea was proposed in [29]. First, we briefly outline the main features of both standards and then proceed with the integration idea.

IEC 61850 decomposes power substation, including functions for monitoring, control and protection and primary devices, down to objects thus obtaining object-oriented representation of the power system. The smallest object is "data attribute" which is encapsulated into "common data" object. These are the data used by devices and functions when they operate. Data and data attribute are the information models for the automation functions and primary devices, which are wrapped into a set and represented as a Logical Node (LN). LNs can be described by the data they consume and produce. The Logical Device can be populated by a number of logical nodes to perform a particular function. In turn, the logical device can perform more than one function. The information exchange model describes information and data exchange mechanism and rules between LNs, logical devices and IEDs or RTUs; it is represented as "services". All logical nodes are organized into groups by their purposes, functions and data they represent. The services are defined to each group, so logical nodes belonging to the same group have the same services available for data exchange. The logical devices are only virtual entities; several of them can be placed into one physical device. Thus the whole substation can be modeled as a set of logical devices populated by logical nodes to perform certain functions. Such a representation structures the power system and standardizes the information capture and exchange, providing interoperability and compatibility of different vendor products used in the power system.

A basic function block (FB) of IEC 61499 is a program component whose behaviour is specified by an event-driven state machine and algorithms, associated with its states. Function blocks can be composed into more complex structures: composite FBs, sub applications and applications which make them appropriate for representation of logical nodes and the multi-layered architecture of IEC 61850. In addition to the structures helping to organize functionality, the IEC 61499 standard provides the means for architecture description. A *resource* is an abstraction for an independent execution container; it can be populated by one or several applications. An IEC 61499 *device* comprises one or several resources, and several networking devices can be grouped into a *system.*

B. Integration of IEC 61850 and IEC 61499 into Intelligent Logical Nodes

In the proposed architecture, for each LN of IEC 61850 an Intelligent Logical Node type is implemented as a function block type, with services represented as event inputs of the function block. Each ILN is modelled as a composite function block that includes three main blocks as shown in Figure 2 on example of the XCBR logical node:

-DataBase, containing data and services of the "parent" LN;

-ServiceInterpreter that parses name of requested service of string type at the time service input event arrives;

-Intelligence – the part responsible for decision making and negotiation with other ILNs, the algorithm the ILN follows (will be discussed in later section).

The interface of the database for the logical node is exemplified in Figure 2 (left side), which represents the structure typical for all modelled LNs. Some interaction directions between the components are shown by arrows.

In IEC 61850, a LN is described by the data termed as Common Data Class. This datum has several attributes describing its different features, such as quality of the data, time stamp of the data, etc. IEC 61499 has "structured data type" class that is intended to represent several characteristics of the same datum. Therefore, we modelled the Common Data Classes defined in [30] as structured data types of IEC 61499. A logical node is also described by communication services operating over the data. Database is a container for all data and services used by the ILN. In Database FB, the services are presented as events which will start the corresponding algorithm implementing the services. Each data attribute has a functional constraint, for instance *"status information"* [31], this means the data is only allowed to be used in the *GetDataValues* service. These constraints are taken into account at the Database design time, so when reusing the database FB, there is no need to pass constraint as a parameter; instead it will be already counted by default according to the standard. The services are associated with corresponding data according to IEC 61850 specification. The output of the Database FB is the result of the services it is executing. Different intelligent logical node types can be organized using the inheritance relation as in object-oriented programming, so more complex nodes can inherit data and services from simpler ones and add new data elements and services.

V. Test FLISR Scenario

In this paper the FLISR scenario from [29] will be used for illustration of the ILN architecture application. The scenario is applied to the simplified typical distribution network shown in Figure 3.

A brief explanation is as follows. The distribution utility consists of three 11kV feeders supplied by three different zone substations. The 11kV feeders are shown in a simplified form, with only the backbone and ties to adjacent feeders.

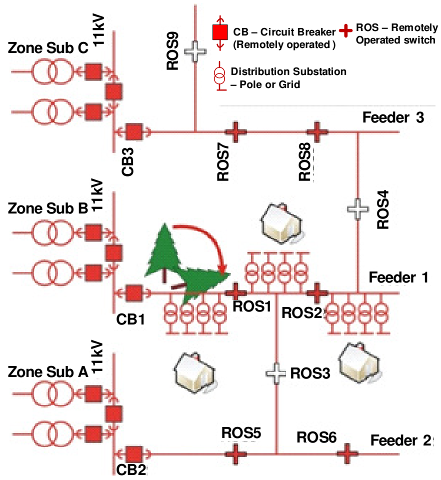

Figure 3. Sample power distribution utility and location of the fault [29].

In reality, 11kV feeders have a branching structure such that the feeder and the associated low voltage feeders can supply a geographical patch. Distribution substations are positioned along each feeder to serve the customers' loads.

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

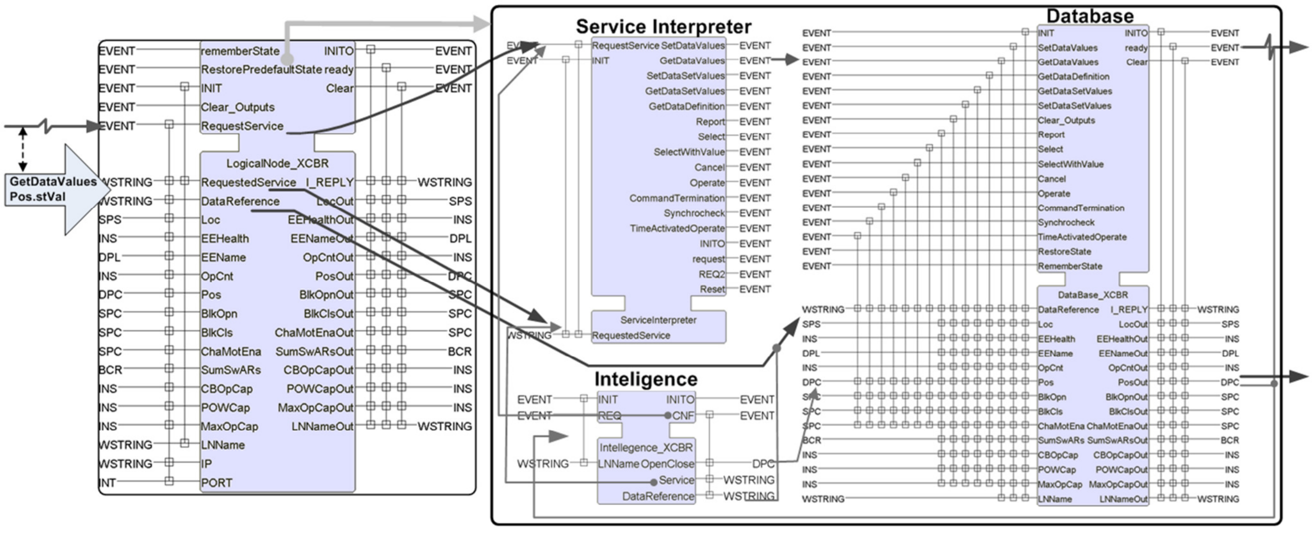

Figure 2. The generic structure of an intelligent logical node.

The scenario begins with a tree falling on the 11kV mains, causing a permanent fault on feeder F1. The feeder protection trips (opens) the 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 re-closure, CB1 goes to lockout.

Tie switches ROS3 and ROS4 realize 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 for help" towards a zone substation. CB2 at zone substation A and CB3 at zone substation C are responding 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 un-faulted 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 be transferred to feeder F2; the tail-section will be transferred to feeder F3; the head-section will have to await repair.

VI. Distribution of Control Functions

The separation of functions (or definitions of the agent's roles) is the main underlying principle for the proposed MAS layered architecture. It is necessary to take into account different requirements in execution time and different scopes of consideration (local, global).

As a first step we allocate substation automation functions (according to IEC 61850) to the instruments of the utility as illustrated in Figure 4.

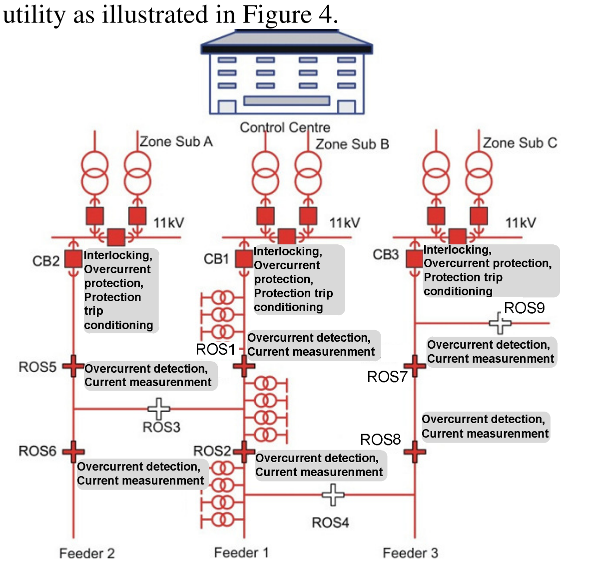

Figure 4. Sample power system substation with intelligent distributed control functions allocated to the instruments.

According to [29] the feeder automation functions are as follows:

1. Protection (Overcurrent) PIOC LN
2. Protection (Protection Trip Conditioning) PTRC LN
3. Protection related (Auto-reclosing) RREC LN
4. Monitoring of circuit breaker XCBR LN
5. Control of circuit breaker CSWI LN
6. Monitoring of Disconnect Switch XSWI LN
7. Control of Disconnect Switch CSWI LN
8. Measurement (current), Monitoring of Current Transformer TCTR LN
9. Interlocking LN.

Figure 5 presents the designed layered architecture. There are three layers (levels): process level, bay level and station level. Process level represents primary devices such as circuit breakers, switches and current transformers, thus this level consists of XCBR, XSWI and TCTR LNs. Bay level performs substation automation functions, monitoring and controlling primary equipment, thus it has CSWI, PIOC, PTRC and RREC. Station level controls whole system and send system level control signals (commands).

As the second step, we represent the utility network in terms of the IEC 61850 architecture, i.e. as LNs. XSWI represents the sectionalising and tie switches, XCBR represents a circuit breaker, and TCTR corresponds to a current transformer. These are information models of primary devices according to IEC 61850. Switches are categorised into 2 types: sectionalising switches and tie switches, differing in purpose and functions. A sectionalising switch divides the substation into sections, so it is easier to locate and isolate faults. Feeders are connected to the adjacent feeders through the tie switches. The sectionalising switches are used to isolate faults, and tie switches to restore the supply to non-faulted sections.

Note that the logical nodes used in this example are extended to implement the additional functionality required by the automatic FLISR scenario.

The substation automation functions have been organized into hierarchy as shown in Figure 5 and commented in the following sub-sections.

1) Process level functions

XCBR and TCTR are simple LNs, representing device specific data and providing services as defined in the IEC 61850 standard. These objects are controlled by the bay level control. TCTR senses the current and XCBR provides status information, changing its state by the command from the control LN. We assume the current transformer (TCTR) to be capable of sensing the current and sending the sampled values to the PIOC.

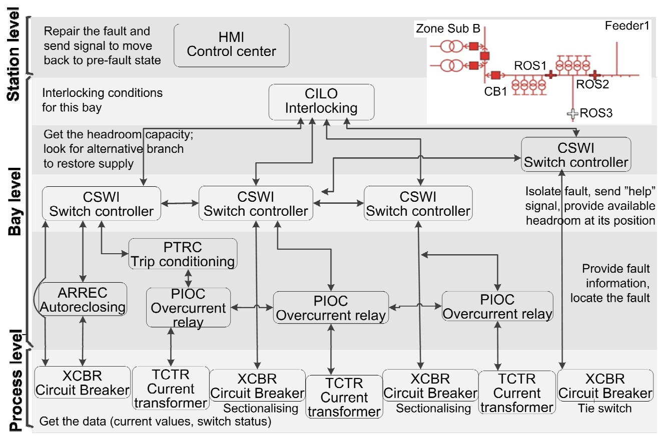

Figure 5. Substation automation functions mapped to LNs, their interaction and tasks for single feeder (Feeder 1).

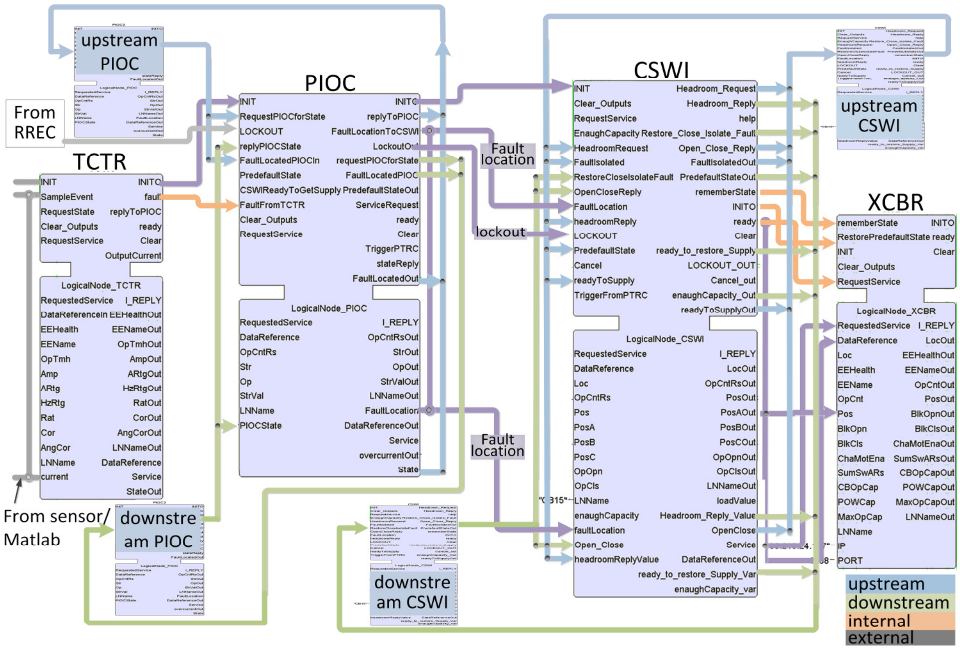

Figure 6. FB control model for the example utility. One IED position is shown (switch).

2) Bay level functions

The bay level functions are divided into three layers and interlocking. Interlocking checks whether the requested switch operation (open/close) violates the network constraints giving the permission to operate if it does not

The first layer of the functionalities is provided by intelligent protective relays, in this case over-current Relays (PIOC). The function of this level is to locate the fault. Once RREC goes to lockout, the "lockout signal" has been transmitted and PIOCs start to collaborate in order to locate the fault. The function of the second layer (CSWI) is to isolate the fault once it has been located, then send the request for alternative supply and provide headroom capacity at the switch position. This is done by collaboration of sectionalising switches. Tie switches on the third layer get a request for alternative supply, initiate search for excess capacity and make a decision whether it is enough to power up the load on faulty section or not, and then offers it to the requested section. Based on the response it will or will not restore the supply.

3) Station level functions

The operator sends the "go back to pre-default configuration" command after the repairing of permanent fault has been completed.

VII. Power Utility Model for Distributed Control

Now, having distributed the control functions, designed the corresponding algorithms (intelligence) and developed the library of LNs, we can model the example utility. In this work feeders are described in terms of IEC 61850 and modelled as a set of ILN from the developed FB ILN library.

As illustrated in Figure 6, the function block model of the feeder includes three switch positions, each consisting of 4 LNs: the switch itself – XSWI/XCBR, switch control CSWI, PIOC - over-current relay, and current transformer - TCTR. For the CB positions at the top of the feeder, there are PTRC and RREC logical nodes added.

Logical nodes representing primary equipment in this set up do not communicate with other LNs on the feeder; they do not participate in the FLISR algorithm. The intelligence and decision making is distributed only across the control and monitoring logical nodes: CSWI and PIOC.

Following our layered architecture, the PIOC layer provides fault information of this section to the next up layer CSWI LN. The PIOC ILN is negotiating with the

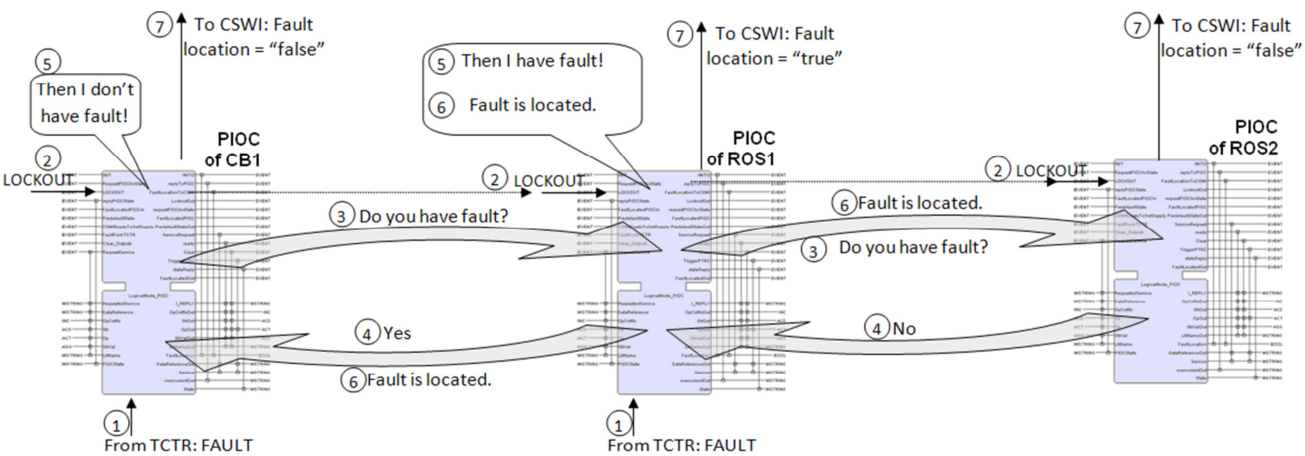

Figure 7. PIOC layer: working of the fault location algorithm (PIOC level of the feeder 1).

peers - downstream and upstream relays - to identify the fault location. The algorithm of fault location and negotiation tactics will be discussed in the next section. The next layer of CSWI LN makes the decision relying on information provided by its PIOC and gathered from the upstream and downstream peer CSWI LNs. For instance, it can negotiate to isolate fault on its own section; or it can ask the tie switch to look for an alternative supply and restore supply based on the situation. CSWI controls a switch or a circuit breaker. In this set up, it opens/closes CB via service "Operate" that requires parameters such as "data reference", "requested service" and the data itself. Additionally, CSWI commands "remember state" to indicate that the state of the feeder has changed, requiring back up of current position of the switch.

VIII. Negotiation Tactics of Distributed Intelligent Components for Achieving FLISR

A. *Fault Location: PIOC level*

Figure 7 demonstrates cooperation of the PIOCs along Feeder 1 in order to locate the fault (the figure shows the communication flow within the system). Assume in this case the fault is on section ROS1. The collaboration for the fault location starts when one of the current transformers TCTR senses the faulty current. First two upstream TCTRs inform the corresponding PIOC about their fault state. The PIOCs await the *"Lockout"* signal which indicates that there is a permanent fault and the power was cut along the feeder. Once the lockout signal has been received the upstream PIOC propagates the signal to downstream PIOC and all PIOCs on this feeder move to the fault state and start their fault location algorithm.

The PIOCs, on receiving the fault status from TCTR, request neighbours' status. If the downstream relay's status is fault, then it is concluded that the fault happened not on this section, but somewhere downstream, that is why the TCTR senses the fault current. If the downstream PIOC has the normal state, which signifies that this section is the last part whose TCTR is sensing high current, the fault must have occurred on this section of the feeder. Step 5 is where PIOCs make decision about fault location. The first upstream PIOC indicates that it does not have a fault, the next downstream PIOC correctly identifies the fault location as being on its section of the feeder and transmits to neighbours that the fault is located. Once all PIOCs are informed that the fault has been located, they report to the corresponding CSWI about fault status on their section.

B. *Fault Isolation and Supply Restoration: CSWI level*

The collaboration starts when a fault occurs on one of the feeders, for instance on feeder 1 (Figure 8) on the position of CB1. LNs implementing the protection functions will play their role and trip the circuit breaker, reclose it and, if the fault is permanent, then the auto reclosing function will go to lockout. The "↑" and "↓" arrows denote the upstream and downstream communication flows respectively

After the fault has been located by PIOC, CSWIs are informed about the fault location (in our example the fault is on CB1 section). The CSWIs which do not have fault on their sections send "help" to tie switches to request search for alternative supply (ROS1 to tie switch ROS3, ROS2 to tie switch ROS4). Tie switch (ROS3) propagates the "Headroom_Request" signal to upstream switches on the non-faulted feeder it is connected (feeder 2). Switches on the feeder 2 reply with available headroom capacity and the tie switch decides if there is enough capacity to supply the requesting section. In case of not sufficient capacity, the

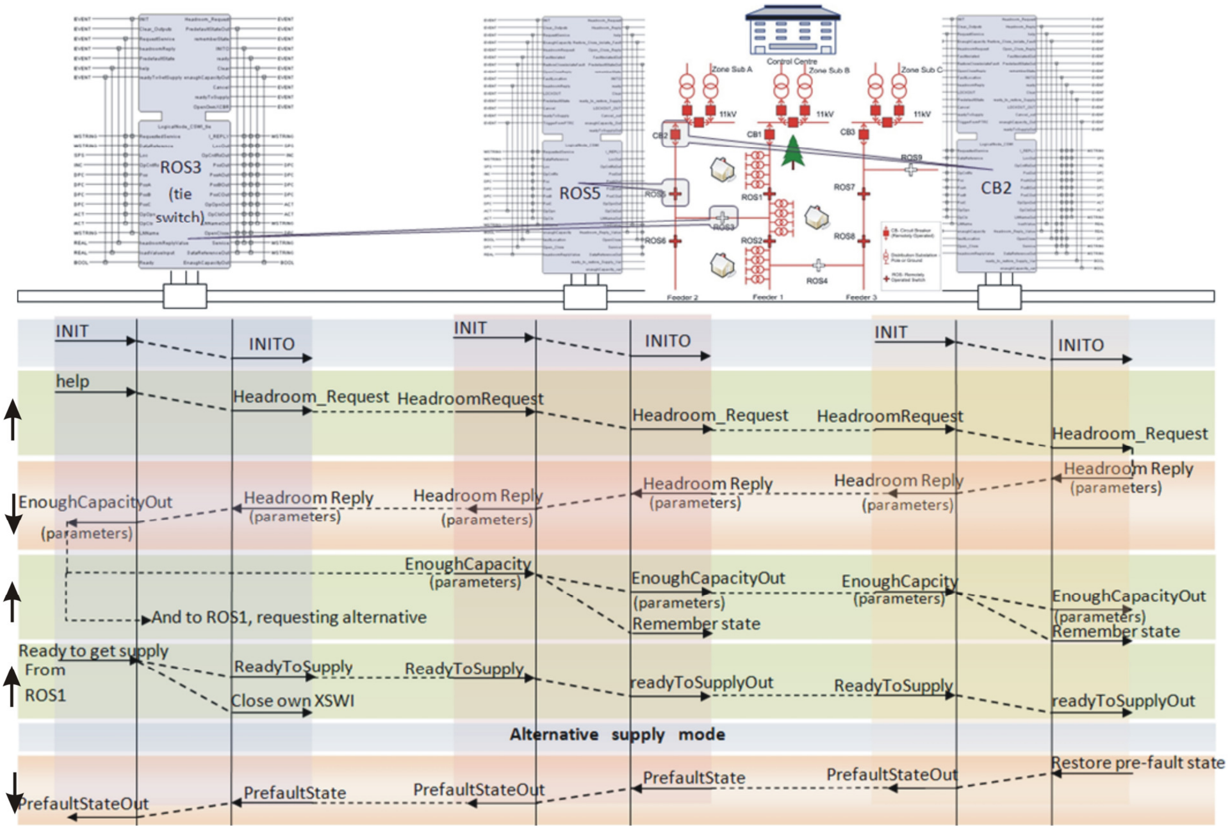

Figure 8. Alternative supply search: trace of the negotiation between logical nodes.

switches come back to the normal state. Otherwise, CSWI on a non-faulted feeder 2 issues the “Remember state” signal to the connected switch (CSWI). As the ROS1, in this case, is ready to get supply, the tie switch transmits the “ready” signal to the upstream switches on feeder 2 and the non-faulted feeder transfers to the “alternative supply” state for the ROS1 section on the adjacent feeder 1. Once the fault has been cleared and the signal to restore the pre-fault state has been received from control centre, all three feeders return to the pre-fault configuration.

IX. SIMULATION ENVIRONMENT AND RESULTS

This FLISR scenario has been validated by simulation. The simulation was conducted using the software tools, which includes Matlab (with “SimPowerSystem” package of Simulink) as a behaviour model of the real world distribution utility, and distributed control system of the utility in FBs, running in parallel with the model in a function block execution environment, as illustrated in Figure 9. An alternative approach to the system validation is hardware-in-the-loop - real-time simulation platform proposed in [11]. For the purpose of this exercise, the developed simulation environment was sufficient; however, it was developed with the intention to involve power utility hardware at a later stage.

In this work we use the Function Blocks Development Kit (FBDK) [32], but our library can be easily ported to other IEC 61499 compliant tools, such as ISaGRAF [33] or nxtControl [34]. The communication between Matlab and FBDK is realized using UDP sockets, following the approach of [35].

To simulate the fault, the “Three phase fault” block was used. The block implements a programmable phase-to-phase and phase-to-ground fault breaker system and can be controlled either from an external Simulink signal (external control mode), or from an internal control timer (internal control mode). In this work the external control mode is used; where the value of control signal 1 indicates that the fault has occurred, and 0 – no fault. Initial value of this input is 0.

UDP communication is implemented by the “xPC Target” package of Simulink, including blocks “UDP send binary”, “UDP receive binary”, “Pack”, and “Unpack”. Thus we can control the fault block and circuit breakers (open/close) and to acquire the current values for detecting fault and later for calculating headroom capacity.

Several tests of increasing complexity were done to verify the correctness of the collaborative control architecture and algorithms. Next we will discuss one of these scenarios, having illustrated them by plots of several system parameters. The first graph is the control signal of the corresponding tie switch with the values: 0 – switch open, 1 – switch close.

The main FLISR scenario is presented in Figure 10. The fault occurs on section CB1, and supply should be restored on ROS1 and ROS2 sections. Figure 10 demonstrates that all three sections of the feeder 1 had normal current before the fault. As it can be seen from the “CB1” graph, the current transformer detects the fault current of value higher than 2000A at about 3.32s and protection function trips the circuit breaker CB1, so current becomes zero at 3.352s.

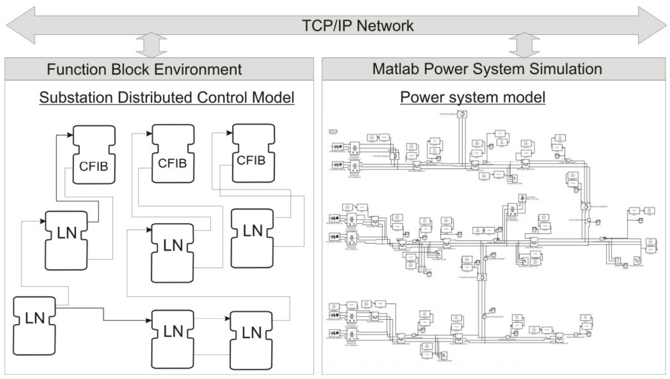

Figure 9. Structure of the testbed combining function blocks control and Simulink model.

The fault on the section CB1 means that the transmission line has been short-circuited phase-to-phase or phase-to-ground, consequently the sections of the feeder below that point will not detect the current passage at all. That is why, at the time 3.32s, when the fault has occurred on section CB1, the graphs, corresponding to the sections ROS1 and ROS2, show that there is no current along the feeder 1 below the fault location. After a certain delay, the RREC LN recloses the circuit breaker at the 3.4s in case it is a temporary fault. However, the protection detects the fault again (the fault current between 3.4s and 3.44s) and trips the circuit breaker, this time RREC goes to lockout.

The “CB1” plot shows that power is cut on feeder 1 at the time 3.44s. The difference between 3.4s and 3.44s is the time to get the signal processed and devices to operate.

Figure 10. FLISR scenario: fault is on CB1 section, supply restored on ROS1 and ROS2 sections.

Meanwhile PIOCs of the feeder has been collaborating to locate the fault and they have agreed that the fault is on the section CB1 having passed that information to the corresponding switch controllers. The switches ROS1 and ROS2 have learned that their sections do not have a fault, so they decide to request the alternative supply: ROS1 from tie switch ROS3 and ROS2 from tie switch ROS4. Thus ROS1 and ROS2 have got the supply from adjacent feeders 2 and 3 accordingly: the graphs “ROS1” and “ROS2” show that at the time around 3.48s the current values come back to normal – the power has been restored. Graph “ROS4” illustrates the behaviour of tie switch ROS4, which closes (at 3.46s the value is 1) as there is enough capacity to restore the supply for section ROS2. Graphs “ROS1” and

"ROS2" demonstrate the supply restoration on the corresponding sections.

This scenario proves that the distributed control of power grid is possible. Autonomous components of power distribution system can collaborate and sustain power grid operation. The components are distributed by nature, and enhancing them with the intelligence makes the system "self-controlled": control is distributed across active elements which are able to interact with the peers and solve the arisen problems. The plots demonstrate that FLISR mechanism carried out by intelligent components of the system without central control intervention works: the supply has been correctly restored on the non-faulted sections of the faulted feeder regardless of the fault location.

The fault has been simulated on every section on each feeder of the sample distribution system, and the agents (ILNs) have successfully carried out the FLISR scenario: the supply has been restored in each scenario (where it is possible, subject to presence of the adjacent tie switch).

X. Conclusion

The reported research is the first step in proving the feasibility of distributed intelligent Smart Grid automation. The proposed integration of two international standards IEC 61499 and IEC 61850 has enabled us to prototype the automation architecture where the intelligence resides on the device level.

The architecture is layered which stems from the IEC 61850 taxonomy. Feasibility of the architecture has been verified on the FLISR scenario. The control and actions of FLISR scenario have been distributed across the number of logic node types. We have demonstrated that the FLISR scenario can be decomposed onto separate tasks that can be performed by each layer: layer of PIOC, performing fault location mission, layer of sectionalising CSWI to isolate the fault and request alternative supply restoration and layer of tie switches CSWI executing algorithm of searching for alternative supply. The layered approach to FLISR control architecture structures the ILNs arrangement in the substation and feeder automation scheme, making the algorithms of the each ILN clear and simple. Each level makes the decisions using the data available and supplies information (result of the decision) to the higher layer. The fault location algorithm is chosen here as it is the simplest to implement and still serves the purpose of our exercise. It is possible to implement any other suitable realistic fault location algorithm.

In this exercise, we focused on the control and collaboration of the intelligent components. The calculation of excess capacity is described in [29], and investigation of other possible ways of excess capacity calculation is in progress. IEC 61499 allows to implement a calculation method of any complexity and to integrate it in CSWI algorithms, without changing the behaviour and control algorithm itself.

The switching sequence during the supply restoration process is crucial to ensure safety and successful restoration. At this stage of the research we assume that the switching sequence is correct in any case, to concentrate on proof of the concept: applying multi-agent technology in device level of power system.

Simulation has been carried out using Matlab SimPowerSystem model as a representation of a real substation, interfacing with Function Block distributed control model through the custom designed UDP sockets. The simulation results have proved and validated the proposed approach. The autonomous distributed intelligent components have successfully carried out the FLISR scenario without human intervention. The implemented ILNs have achieved the successful fault isolation and supply restoration by collaborative behaviour. Simulation has shown that the tasks have been defined and assigned to ILNs correctly and the intelligence of each LN has been designed successfully.

Therefore, this paper has demonstrated that self-healing of Smart Grid is achievable through distributed intelligent control utilizing the advanced ICT. The intelligence is added as an extra layer extending the capabilities of substation automation devices and not interfering with the safety critical functions [36].

Future work will be in the direction of adding more intelligent functionalities (e.g. dynamic load), extending the range of supported logical nodes, developing the system considering more realistic data. Also the future work will identify the list of criteria of distributed intelligent components operating in power system domain. We plan to extend the intelligence to consider energy production by distributed power generators and consumption. We will also attempt prototyping the devices compliant with our architecture, and experimenting with application of the proposed approach on a real utility, which includes verification, realisation requirements and measurement of real-time performance.

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XII. References

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List of Acronyms

BAG – Bus Agent
CB – Circuit Breaker
CSWI – Control of switch LN [7]
DG – Distributed Generation
FLISR – Fault Location, Isolation and Supply Restoration
FAG – Facilitator Agent
FB – Function Block
FBDK – Function Block Development Kit
ICT –Information Communication Technology
IEC – International Electronic Commission
IED – Intelligent Electronic Device
IEEE – Institute of Electrical and Electronics Engineers
LN – Logical Node
PIOC – Protection, Overcurrent Relay LN [7]
PTRC – Protection Trip Condition LN [7]
RES – Renewable Energy Sources
ROS – Remotely Operated Switch
RREC – Protection related, Auto-Reclosing LN [7]
RTU – Remote Terminal Units
SSD – System Specification Description
TCTR – Current Transformer LN [7]
UDP – User Datagram Protocol
XCBR – X – primary equipment, Circuit Breaker LN [7]
XSWI – X – Primary equipment, Switch LN