A Case Study of Multi-Agent Interoperability in IEC 61850 Environments

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Abstract—The IEC 61850 is the most promising standard for design of substation communication and automation systems. On the other hand multi-agents systems are attracting growing interest for different applications of substation automation systems. In multiagent systems agents represent different stake holders in the power system and based on implemented decision making logic they determine optimal operational conditions for the power system’s given boundary conditions. Interoperability is of course a necessary pre-requisite for such architectures. Here we identify two aspects of interoperability; horizontal and vertical. Horizontal interoperability is relies on common semantic models of the power system that the agents can use to make decisions. One such semantic model is presented in the IEC 61970 Common Information Model (CIM). At this level, the IEC 61850 standard provides a model for access to information and control functions that has the necessary flexibility needed. In this paper we discuss the mapping between a multi-agent based architecture for power system control and the IEC 61850 standard for utility automation. The mapping is based on a use-case drive approach, in which the information exchange need is defined by the multi-agent system.

Index Terms— multi-agent systems, power systems control and protection, industrial application multi-agent systems, power systems control and protection, industrial application

I. INTRODUCTION

The development towards a sustainable energy system in the electric power industry has lead to the emergence of a set of market models and new concepts for optimized operation and control of power systems, e.g. Virtual Power Plants and Microgrid. In these new concepts, the traditional stake holders are complemented by new actors that take roles such as aggregator, prosumer, dispatchable load etc. Common to all these concepts is that they assume a more flexible and loosely coupled ICT system architecture. In such architectures, ICT components communicate to implement optimization, control and protection functions. One approach to such architectures is the use of multi-agent system. The agents represent different stake holders in the power system and based on implemented decision making logic they determine optimal operational conditions for the power system given boundary conditions.

Interoperability is of course a necessary pre-requisite for such architectures. Here we identify two aspects of interoperability; horizontal and vertical. Horizontal interoperability is relies on a common semantic models of the power system that the agents can use to form decisions. One such semantic model is presented in the IEC 61970 Common Information Model (CIM). The CIM has the constructs necessary to represent knowledge about the complete power system that the agents need for optimized decision making. Vertical interoperability is concerned with making the agent-based architecture interact with contemporary automation, protection and control systems in substations and power plants. At this level, the IEC 61850 standard provides a model for access to information and control functions that has the necessary flexibility needed. In this paper we discuss the mapping between a multi-agent systems MAS based architecture for power system control and the IEC 61850 standard for utility automation. The mapping is based on a use-case drive approach, in which the information exchange need is defined by the multi-agent system. Based on this need, interaction patterns with logical nodes (LN) as defined in the IEC 61850 are identified. The mapping also enables interaction at different levels of abstraction with the IEC 61850 based systems.

Rest of this paper is organized as follows:
Section II introduces fundamental concepts of agents, multi-agent systems, IEC 61850 and related standards. It also introduces the problem of protection and control in electric power systems with distributed generation which provides the study case used in this paper. Section III describes our approach for MAS to IEC 61850 mapping. Section IV presents application of our approach in a study case and discusses the results. Section V concludes the paper.

II. RELATED WORK

This paper combines the formalisms of agent-based control with the nomenclature of IEC 61850. In this section, these
topics are dealt with separately after which other work that combines them is discussed.

A. Multi-Agent Systems

The fundamental concept of software agent is defined as:

*An agent is an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in that environment to meet its design objectives.*[10]

Agents are elaborated by a metaphor commonly known as BDI (Belief, Desire, Intention). Beliefs represent knowledge of an agent about its environment. The Beliefs are captured through sensors of the agent and stored in an internal data base. This data base (also commonly called knowledge base) should be properly organized, updated and synchronized to other functions, e.g., decision making of the agent architecture. The Desires are goals or design objectives of an agent (or of the systems agent is part of). Desires not only sets the criteria for rationality of an agent but also defines the nature and level of autonomy for agents. Intentions is the way agents attempt to achieve their design goals. In agent oriented software engineering intentions are modeled as behaviors. A behavior of an agent may consists of a single or multiple actions and lead to a achievement of a goal or a sub goal.

Multi-agent systems (MAS) are systems consisting of more than one agent. MAS are useful to implement in application areas that are naturally distributed, decentralized and are easy to be decomposed in their design. A system architecture based upon MAS provides a natural way of decomposing a software system into subsystems and to model interactions between these subsystems and individual components (agents) within the subsystems.

B. Protection and Control in Electric Power Systems with Distributed Generation

Introduction of distributed generation in medium and low voltage grids has brought challenges in functions of protection and control. New approaches suggest increasing use of modularity and communication. The methods presented in [6], [9], [5], [8], [4], [7] are among many works that propose the use of multi-agent systems for protection and control in electric power systems. Both [6] and [9] propose methods that utilize agent-based zoning for use in distribution networks. In these schemes, agent-controllers are placed at the zone borders and at DG sources within the network. By interactively comparing measurement data and coordinating effector capabilities at different locations in a distribution network, various protection, monitoring and control functions can be implemented. Such distributed functions can include fault location and restoration [9], [4], current differential protection [6], islanding [7], adaptive load shedding [2] and voltage regulation [8].

C. IEC 61850 and related standards

The IEC 61850 series of standards for communication networks and systems is intended to provide interoperability between Substation Automation Systems (SAS) [1]. It provides a specification for the communication between Intelligent Electronic Devices (IEDs) and related SAS equipment. Furthermore, it describes the requirements of the functions implemented in SAS, not to attempt to standardize the functions themselves but to specify the communication between them.

A subset of the functions that are described in [1] fall into the category of distributed functions. The standard defines these as the set of functions where it’s subparts, called Logical Nodes (LNs), are located on different physical devices. While all functions communicate with each other, the process that they are controlling, monitoring or protecting, distributed functions are dependent on the execution of a set of defined functional steps for their functionality. The loss of any of the constituent LNs could mean that the function would be blocked or that it would be functionally degraded.

The IEC 61850 standard also defines a functional hierarchy where functions are classified in terms of how closely they are situated to the substation process. Three main levels are defined:

- **bay level functions** - refers to the group of functions that are predominantly associated with a specific bay in the substation instance.
- **process level functions** - interface directly with the process, namely I/O functions such as data acquisition and issuing of commands.
- **station level functions** - refer to functionality that concerns the substation as a whole.

Figure 1 from [1] illustrates the functional hierarchy as well as shows the numbering of the standard interfaces between
LNs in different levels and between LNs situated on the same functional hierarchy level. Interfaces 2 and 10, shown in gray, are not defined in the standard. Interface 2 is reserved for use in remote protection functions on the same level on the control plane while interface 10 is the undefined vertical communication to SCADA or other remote control. The specification of communication via the remaining interfaces is the core of the IEC 61850 standard.

Communication between LNs at the station and bay levels occurs through interfaces 1 and 6, while between LNs within a station or bay are 9 and 3 respectively. Interface 8 supports direct communication between LNs in different bays, this is used to support functions such as interlocking.

Finally, interfaces 4 and 5 provide the communication channel between process and bay level functions. The use of a process bus specified in IEC 61850 is discussed in detail in [3]. The benefits that are pointed out are the increased level of interoperability between low-level devices that is achievable as well as the possibility for cost and operational optimizations that are not possible using more traditional methods where extensive copper wiring is required.

D. Multi-Agent Systems and IEC 61850

General objectives of this paper is similar to that of the work done in [2] which proposes the view of IEC 61850 and CIM to provide a standardized framework for application of MAS to electrical power protection, control, monitoring and recording. In [2] the author proposes a 1:1 mapping of agents to LNs in a SAS. Vertical interoperability is achieved by implementing LN functionality as an agent while the horizontal agent interoperability is by definition maintained. Agents are categorized by the functional level at which they are placed, these include the process, logical device, bay and substation level. The type of inter-agent communication and the interfaces used are defined by the functional level at which the distributed function implemented by the MAS is situated.

III. MAS TO IEC 61850 MAPPING

When considering the method for the extension of [2] in this paper, we use [9] as the basis for deployment of agents and the assignment of agent functionality. Figure 3 illustrates the agent placement used in the example in [9] that is described in section IV where a Distributed Generation (DG) agent is placed at each DG source and a relay agent is deployed at each zone border. The geographical locations of the the agents are also the location of the host physical devices or servers as they are referred to in [2].

The horizontal communication in the functional hierarchy occurs through logical interfaces 2, 3, 8, 9 and 10. All except interfaces 2 and 10 are specified by the IEC 61850 standard for communication between LNs. Interface 2 is allocated for implementation of remote protection functions. This bay-level horizontal communication should by definition be both reliable and low latency. The remote control interface 10 for vertical communication is intended for communication with SCADA or other high-level control.

The formalism proposed here is that a set of LNs are implemented in each MAS agent, this allows MAS integration to remain consistent with the IEC 61850 standard. More specifically, LNs that are implemented in the MAS (mostly at the station functional level) appear as standard LNs to all other LNs and communicate via the same interfaces using the protocols specified by the IEC 61850 standard. This allows complex distributed functions to utilize the cooperative, autonomous and pro-active capabilities of MAS-based control interoperably with IEC 61850-based SAS.

A. Roles and control plan

The control strategy presented in [9] specifies that an agent can assume a set of different roles. These roles fill different functionalities defined in a control plan. The role assigned to an agent can change due to changes in the state of the system control plan such as disappearance of an agent, appearance of a new agent, changes in agent capability, external trigger events or scheduled activities. The roles assumed by the agent and LNs assigned to each role are defined in the control plan.

The processes of generating a control plan and allocating roles proposed in [9] makes use of a transition function. The transition function maps a control plan, defined as a set of related roles, to specific world situations. The transition function is based on domain principles such as the laws of electromagnetism and control theory. Transitions are determined at design time. At run time, role assignment to agents based on the transition function are determined by means of an auction mechanism. A coordinating agent mediates the communication required to perform the role assignment. The assignment and realization of the roles to agents depends on the capabilities of the agent physical host devices.

B. Logical Node Assignment

Depending on the required functionality of the agent, sets of LNs that implement the functionality must be assigned to it accordingly. IEC 61850 LNs are selected such that they form the low-level "atomic" functional units of control, monitoring and protection. Each agent must therefore implement IEC 61850 LNs for all of the low level functionality required by all roles that the agents are capable of assuming. Not all LNs are used simultaneously, different subsets of an agent’s LN set are used depending on the current role.

The LNs that the agent is capable of implementing will depend on the capabilities of the agent host physical device as well as which LNs lower in the functional hierarchy it can communicate with. Figure 2 illustrates the relationship between the agent itself, the roles it can assume, the LN set associated with a specific role and finally, how the
Fig. 2. Illustrates how an agent can assume various roles containing a set of LNs each which use different capabilities.

LNs are interact with the capabilities of the physical host device. Communication between LNs strictly follows IEC 61850 specification using for instance, logical interface 3 if the communication occurs between bay-level LNs in the same bay or interface 8 if the communication is between bays.

The scope of the functionality available to an agent LNs is determined by the capabilities accessible to the agent. Most of the capabilities are enabled through the process level LNs like XCBR, TVTR and XSWI. These LNs do not need to be implemented on the same device but need to be in communications with the agent physical host device using the IEC 61850 specified process interfaces. Communication between the process level LNs and bay level LNs occurs through the process bus labeled as IF4 and IF5 in the standard. Some bay level function LNs could be implemented by IED bay controllers as per the current norm while more complex distributed functions become well suited to implementation as agent LNs.

This method is consistent with the IEC 61850 standard for substation automation but allows complex functionality or functionality where stakeholders should be represented to be implemented on an agent platform that supports a high level of local control intelligence incorporated into LNs as well as the ability to negotiate and cooperate with other agents. Some larger distributed function LNs could be implemented on a group of individual but related agents while similarly, a group of closely related LNs could be implemented on a single agent platform logical device.

IV. EXAMPLE AND VALIDATION

In order to describe and validate the mapping formalism presented here, we apply it to the example agent-based protection and control scheme presented in [9]. Beginning with a brief explanation of agent decision models and description of the agent types used in the system. The protection and control system model is then mapped to the IEC 61850 formalism described in the preceding section.

A. Agent Decision Models

This subsection describes the decision models of three types of agents.

1) Relay Agent: The relay agent has a central role in proposed schema. There is one Relay agent at the start and end of each zone in the network e.g. R2 and R3 for zone II. They continuously monitor the state of the network, identify and respond to any changes or transition triggers. Relay Agents work as zone disconnecters with responsibility to separate a zone from the network. In normal condition, there is a steady state current flowing into the network and whenever a fault occurs due to, e.g., a short circuit, a high current (fault current) flows into the network. The value of this fault current is significantly higher than the normal current value in steady state. The relay agent gets triggered upon observing an unusual high current value and has three main tasks:

i: Direction of fault current:

In a fault scenario, current always flows form the current source to the fault location. Thus, to ensure that fault is inside the primary zone of a relay, the relay agent has to
TABLE I
DESCRIPTION OF AGENTS, STATES, ROLES AND CAPABILITIES

<table>
<thead>
<tr>
<th>Agents</th>
<th>States</th>
<th>Roles</th>
<th>Capabilities</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td>stressed, average, relaxed, disconnected</td>
<td>generator, regulator</td>
<td>produce power, freq. control</td>
<td>P++, P- - disconnect, reconnect</td>
</tr>
<tr>
<td>Relay</td>
<td>faulted, functioning, faulted-zone, cleared-zone</td>
<td>primary facilitator, neutral, blocked</td>
<td>monitor current, monitor voltage</td>
<td>close, reclose(open)</td>
</tr>
<tr>
<td>Load</td>
<td>critical, non-critical</td>
<td>connected, disconnected</td>
<td>self-shed</td>
<td>(re)connect, disconnect</td>
</tr>
</tbody>
</table>

make sure that the direction of the fault current is into its primary zone at two zone connecting breakers i.e. the breakers which connect a zone to its neighboring zones, and at the DG connection breakers for all DGs inside the zone.

ii: Magnitude of fault current:

The relay agent has to ensure that one of the fault current measurements either from the zone connecting breakers or from the DG connecting breakers is greater than a certain threshold. This is necessary because in case some of the loads in the zone are served from DGs outside the zone, the current flows into the zone even in normal situation when there is no fault.

iii: Role assignment:

After a fault has been confirmed inside one of the zones, the job of each relay agent with the zone of its primary responsibility isolated from the main grid is to calculate energy balancing in its primary zone and assign new roles to DGs and loads inside the zone. This requires calculation of total generation and consumption of energy inside the zone and negotiation with DG and Load agents for participation in balancing. DG agents and Load agents calculate local cost functions based upon their current state and capabilities and communicate it with Relay agent. The relay agent based upon the value of cost function of each of these agents assigns them new roles. Thus, the job of Relay agent, in this case, is to determine a mapping function that takes current state and maps roles to specific agents based upon their capabilities, i.e.,

\[ f_{tr}(S_{cur}, T_i, CP_{ini}) \rightarrow CP_{fn} \]  \hspace{1cm} (1)

Where \( f_{tr} \) is the function that takes current state \( S_{cur} \) and a transition property \( T_i \) to map a chosen control plan \( CP_{ini} \) into a final control plan \( CP_{fn} \) with all roles assigned to specific agents. \( T \) is the set of transition triggers described in the previous section. Figure 4 describes the decision model of Relay agent.

2) DG Agent: DG agents represent distributed power generators in electrical network. Every DG agent, on receiving message from Relay agent, calculates its cost function. The
The cost function of DG agent is based upon its current state e.g. relaxed/average/stressed, and its capabilities e.g. ability to control frequency. The cost function of a DG agents is defined as:

\[ \delta_c(S_{cur}, C_{cur}) \rightarrow U_{role} \] (2)

i.e., the cost function is a function that maps current state of DG agent \( S_{cur} \), and current capabilities \( C_{cur} \) into a role utility \( U_{role} \). DG agent sends a bid based on the value of this cost function. Relay agent cumulates bids from all DG agents and sends back a message with a new role. DG agents upon receiving this message takes up the new role and start executing actions related to this role. A flow chart for decision model of DG agents is given in figure 5.

\[ \delta_c(S_{cur}, C_{cur}) \rightarrow U_{role} \]

After calculation of the cost function, load agent sends a bid based upon value of this cost function to Relay agent. Relay agent cumulates bids from all Load agents and sends back a message with a new role. Load agent on receiving this message takes up the new role. The decision model of load agents is same as that of DG agent with only difference of different set of capabilities and current states. Different possible states, roles, capabilities and actions for Relay, DG and Load agents are described in Table I.

B. MAS Protection and Control Mapped to IEC 61850

This section details the allocation of LNs in order to model the protection scheme from section IV-A. We begin by describing the LNs that are of interest after which the LN assignment and interaction is described.

The deployment of the various agents is shown in figure 3. For the Relay agents we assign the station-level LNs RFLO and PDIF, Load agents are assigned PIOC and MMTR while DG agents are assigned ZGEN and ARCO as shown in Figure 7. Relay agents are placed at the zone borders in order to monitor and control up and downstream flow from the zones.

Figure 6 shows the IEC 61850 style model of the collaborating parts of substations B1 and C1. It presents a modified version of figure 15 in the IEC 61850 standard which illustrates the LNs that define a distributed busbar protection system for a single substation. To illustrate the mapping onto the test scenario presented in this paper, the example is expanded to include two electrically connected substations which interact with each other in order to implement a distributed fault location LN RFLO.

In this case it makes sense to implement the lower level (process and bay level) LNs in dedicated logical device hardware such as IEDs and MUs . The closely related station level PDIF and RFLO LNs are collocated on the relay agent platform. The distributed function RFLO requires agent capabilities such as communication, negotiation, data consistency/quality management and intelligent pro-active control. The interaction between agents uses agent communication language (ACL) and utilizes the utility’s IP-based wide-area-network for communication.

The process level LNs define the sensor and actuator equipment at the process level, a current measurement transformer in the example. Process level LNs are likely to use merging units (MU) as logical devices . Current samples are collected at process level and send via the process bus (most likely using GOOSE or GSE messages) to bay controller logical devices that are subscribers to the current sample data. Bay level LNs could be assigned to dedicated fast-response logical devices, they often include protection and safety functions.

\[ \delta_c(S_{cur}, C_{cur}) \rightarrow U_{role} \] (3)
Fig. 6. Decomposition of functions into interacting LNs on different levels showing agent LN interaction.

Fig. 7. Showing the mapping of high-level LNs to agents in zone C from Figure 3.

which must be verifiable in terms of reliability and response time. Station level LNs are more likely to require a high level of interaction and therefore are in some cases best assigned to agent platform based logical devices where distributed functions can be implemented across a set of agents.

By modeling the structure and communication of multi-agent functionality using IEC 61850 nomenclature there is the potential for seamless interoperability between modern SAS best-practices and sophisticated distributed intelligent control.

V. CONCLUSIONS

In this paper we have shown the applicability of multi-agent systems for control and protection in electric power systems can be augmented by the integration of IEC 61850 communication principles.

Applying the IEC 61850 functional hierarchy allows SAS design engineers the flexibility to make optimal choices in terms of the allocation of dedicated hardware for predictable response times or integration of functionality in general hardware to save costs and allow for integration for high-level distributed control.
Traditionally, the protection systems in electric power industry have utilized very little communication. With the adoption and integration of IEC 61850-enabled devices and the development of powerful, reliable distributed intelligent control methods that inter-operate transparently with these devices, the goal would be to realize a robust, scalable, secure and interoperable future electric power transmission and distribution system that adheres to well-developed and intuitive standards and best practices. We have therefore provided a mechanism which is robust to communication failure. In the worst case of total communication failure the result will be as good as that of from current common practice.

REFERENCES