An intelligent multi agent framework for active distribution networks based on IEC 61850 and FIPA standards

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An Intelligent Multi Agent Framework for Active Distribution Networks Based on IEC 61850 and FIPA Standards

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Abstract— **The development of a resilient and intelligent smart grid concept with decentralized control capability requires extensive deployment of interoperable frameworks. This paper presents a global multi agent framework using IEC 61850 and the foundation for intelligent physical agents (FIPA) standards. The developed framework was implemented on a laboratory based smart grid test bed at Florida International University. The open connectivity unified architecture (OPC UA) interface was adopted to share common information between two platforms. The hardware/software based Smart Grid Test Bed involves actual IEC 61850 intelligent electronic devices (IED) and a complete hardware based laboratory setup. In order to present the capabilities of the developed framework, an autonomous distributed energy resource (DER) ancillary service use case was realistically demonstrated as a sample study.**

Index Terms— **FIPA, IEC 61850, JADE, Multi agent, OPC UA**

I. Introduction

In contrast to centralized control in existing grid , the emerging smart grid concept compels utilities to adopt decentralized methods as a result of the highly dynamic behavior of the active distribution networks. Decentralized control approaches intend to provide autonomy for different control layers by enabling an event-driven peer-to-peer communication structure, where central control schemes mainly rely on master-slave interactions. In power system applications, the implementation of decentralized control is established using multi agent frameworks, which are composed of interacting multiple intelligent agents to achieve a global or local objective function. An agent requires interaction with its environment through sensors and actuators. A sensor acquires the data from the outside world and the actuator responds according to the agent's decision. Embedded decision making algorithms facilitate the benefit maximization of the agents' autonomy.

Multi agent based schemes are widely applied to power system controls; including self-healing, resilient grid automation [1]-[2] and power system protection [3]-[4]. Multi agent based microgrid control draws considerably more attention than any other smart grid applications [5-10]. For actual implementation of decentralized control schemes in power systems, it is imperative to link multi agent objects to distributed industrial control systems such as intelligent electronic devices (IED) and programmable logic controllers (PLC).

The required interface is established through the combination of the information data and protocols.

Interoperability is one of the major challenges to accomplish a complete smart grid infrastructure due to the large amount of processed data from different vendor and communication protocols [11]. Utilities and independent system operators seek the most proper way to reach the required information easily and securely for different application layers, such as metering, protection, automation and market segments. For this reason, *The NIST Framework and Roadmap for Smart Grid Interoperability Standards Release* [12] defines three major goals to establish interoperability standards and protocols for the smart grid. The *IEEE Std. 2030* establishes three integrated architectural perspectives: power systems, communications technology, and information technology [13]. The guidelines also define the design criteria, and reference model applications with communication connections and data flows [14].

IEC 61850 is the new international standard of communications, which enables the integration of all substation functions, such as protection, control, measurement and monitoring. IEC 61850 expands the area of influence in many parts of power systems due to its wide industry acceptance. Communication systems for hydroelectric power plants and distributed energy resources (DERs) have been recently applied to other domains as IEC 61850 extension standards [15]. However, the smart grid concept covers an extensive control, automation and protection applications such that a single standard may not meet all the required forms of monitoring and information exchange demands.

Considering the emerging active distribution networks, new energy market policies are necessary such as implementation of real-time auction models and scheduling the dispatch of DERs. Hierarchical control of microgrids require interaction with utilities for dynamic adjustment of the primary, secondary and tertiary control levels. Taking into account the mentioned requirements of the future grid, advanced intelligent multi agent frameworks are necessary with a flexible ability to create tailor-made decentralized control schemes while allowing the legacy protocols.

The foundation for intelligent physical agents (FIPA) is an organization which intends to evolve inter-operable agent communications with semantically meaningful messages, such as how messages are transferred and presented as objects [16].

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Java agent development framework (JADE) is a software framework to develop agents compliant with FIPA standards with flexible agent behavior methods [17].

Taking the specific benefits of two major frameworks, this work intends to provide a flexible intelligent multi agent framework for all power system application layers, merging the IEC 61850 and FIPA standards by using the open connectivity unified architecture (OPC UA) interface. To date, few researchers have contributed using multi agent systems with industrial devices where most of them have presented their work in simulation environments. This contribution is intended to extend existing works to a hardware-based laboratory environment within an actual smart grid test bed.

The outline of the paper is as follows. Section II discusses the related work and contribution of this work. In section III, the developed cyber-physical framework is explained in detail. An experimental case study is demonstrated in Section IV. Section V concludes the paper.

II. Related Work

The integration of IEC 61850 and OPC UA provides an opportunity to extend interoperability with different information domains in a standard format. In [18], a hierarchical control, monitoring and diagnosis applications for smart grid automation were presented. A JADE multi agent platform was linked to PLC and distributed control system (DCS) field devices using OPC DA (Data Access) servers for maintenance planning system and repairs on monitored industrial devices [19]. An internet-of-energy based virtual power plant (VPP) controller scheme was proposed using IEC 61850 and OPC UA semantic services [20]. The proposed model is composed of physical electric grid assets, a communication network, ontology layer and service layers. In [21], an autonomous regional network management system with its own multi-agent system application known as the AuRA-NMS was proposed. The platform was developed in partnership between several UK universities, distribution network operators and equipment manufacturers. A modular agent-based smart grid simulation platform *mosaik* was proposed [22]. This platform allows for large-scale deployment tests of smart grid concepts. In [23], the extension of this simulation platform utilizing the OPC UA interface was presented. Unfortunately, none of the listed references address the hardware-in-the-loop control challenges. With this motivation, this paper presents a state-of-the-art framework platform using IEC 61850 and FIPA standards.

III. Cyber-Physical Framework

A cyber-physical framework consists of physical and cyber components. Actual physical components are the sensors, actuators, generation units, circuit breakers and distribution lines. Cyber components are the data informational representation of the actual physical models with a standardized protocols. This section briefly explains the hardware and the data information model of the proposed framework.

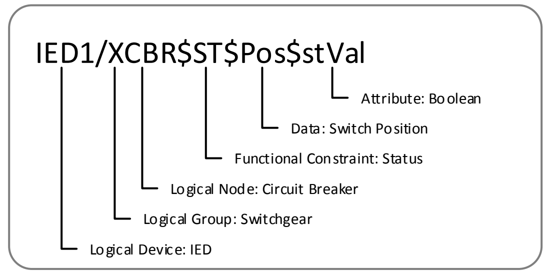

Fig.1. Object name of a circuit breaker position value

A. IEC 61850 Framework

When it comes to interoperability in a smart grid, IEC 61850 is the most promising standard for future grids. Self-describing devices and object-oriented peer-to-peer data exchange capabilities are the most significant superiorities of IEC 61850 over the other common standards. The use of names for all the data, virtualized models, standardized configuration language, lower cabling and transducer installation costs are some of the numerous key features and benefits [24]. Logical nodes (abstract data objects) are the main elements of IEC 61850 object oriented virtual model, which consists of standardized data and data attributes. IEC 61850 defines the abstract communication service interface (ACSI), which creates objects and services independent of any protocols. This enables a hierarchical class model, in which all class information, services that operate on these classes, and associated parameters can be accessed from a communication network [25]. The abstract interface allows the data objects to be mapped to any other protocol, such as manufacturing messaging specification (MMS) protocol and sampled measured values (SMV) protocol on Ethernet data frame.

The virtual model aims to express a physical (logical) device and number of logical nodes. IEC 61850 standardized 91 logical nodes into 13 logical groups. Each logical node contains data elements (DATA), which are standard and related to logical node functions. Most of the data objects are composed of common data classes (CDC), which involves basic data objects, status, control, and measurement. Each data element consists of a number of data attributes with a data attribute type (DAType) which belongs to functional constraints (FC). Fig.1. shows a sample anatomy of an object name for a breaker position value. A physical device is defined by a network address.

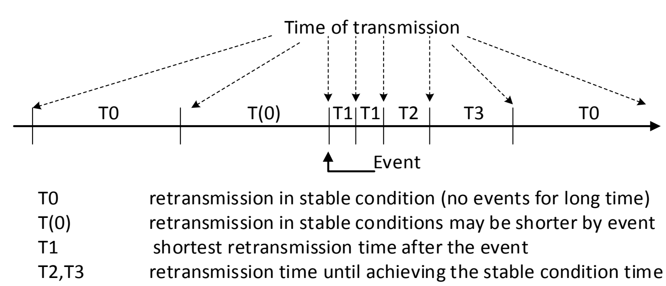

Fig.2. GOOSE messaging [26]

Generic object oriented substation events (GOOSE) is a multicast model based on a publisher-subscriber mechanism within the IEC 61850 framework, which ensures fast messaging with a 4 ms period of time.

GOOSE messages are periodically sent from the publisher IEDs to subscribers with *To* retransmission time period. Should an event occur related to GOOSE control, a new message is generated momentarily, then the message is continuously retransmitted with variable time periods ($T_1, T_2, ..., T_n$) until it reaches the *To* value again as shown in Fig. 2. This retransmitting scheme ensures the appropriate level of reliability. The fast messaging capability of the GOOSE model is widely used in modern power system protection applications, bringing forth a new era of advanced high speed peer-to-peer communication. The details relating to the GOOSE model of messaging is out-of-scope of this work, thus further information can be obtained from the related standard [26].

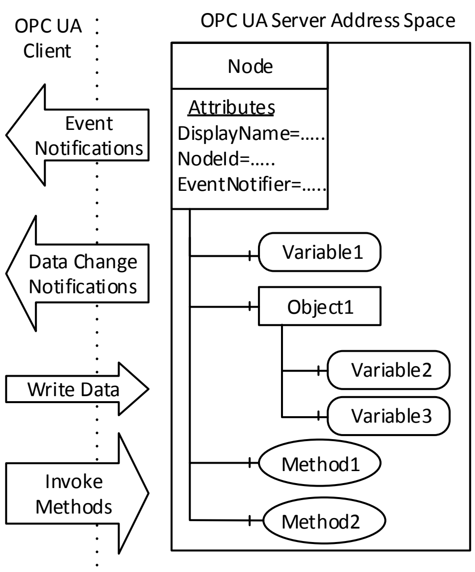

Fig.3. OPC UA nodeclass [27]

B. OPC UA

OPC was originally utilized to abstract various PLC protocols into an interoperable interface for a secure and reliable data exchange. The advent of smart grid interoperability efforts led to the development of OPC UA, which keeps all the functionality of the original OPC Data Access (DA), but switches from Microsoft-COM/DCOM technology to state-of-the-art web services technology. OPC UA is not directly compatible with the classic OPC since they use different technology. OPC UA uses a framework based on client and server architecture, in which the server provides real-time data to clients. Moreover, it can be implemented with Java or .Net platforms eliminating the need to use Microsoft Windows based platforms. This provides a perfect opportunity to model multi-agent based systems on Unix/Linux systems. The OPC UA modeling is based on nodes and references between the nodes. A node can have different sets of attributes connected through references. A *nodeclass* is composed of *objects*, *variables* and *methods*. A variable contains the value which clients can read, write and subscribe to the changes of the value. A method is similar to a function called by client and returns a result. The OPC UA address space is structured with objects containing only the node attributes. Further information can be obtained from the reference [27].

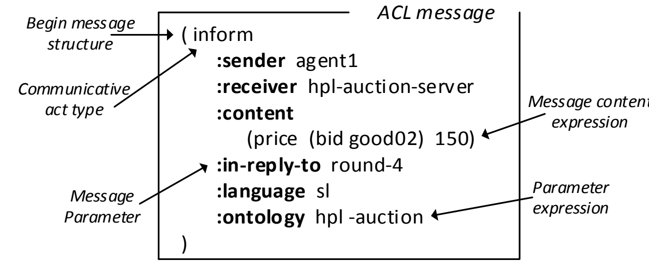

Fig.4. ACL message components [28]

C. FIPA Specifications and JADE Platform

An agent is an interacting object with its own thread of control that operates autonomously. The ideal agent is also expected to have semantic interoperability based on internal decision making [17]. The standardization of agent-based technologies is an ongoing research that few standards have yet to realize to its fullest potential. FIPA specifications help to allow an easy interoperability between agent systems with agent communication language and transport level protocols. Agent communication language (ACL) represents a communicative act or messages intended to perform some action, with precisely defined syntax and semantics. Fig. 4 shows the components of a sample ACL message.

The beginning message structure of an ACL message expresses communicative acts such as (inform, request, refuse etc.). Sender and receiver parameters designate the name of the sender and intended recipient agents, respectively. Content involves the object of the action and parameters passed through the message. Message parameters define the expression of the agent responding to received messages, and which parameter is sent through the message.

The JADE (Java Agent Development Framework) platform is based on FIPA specifications which enables developers to create complex agent based systems with a high degree of interoperability using ACL messages [29]. A JADE agent, at its simplest, is a Java class that extends the core agent class which allows it to inherit behaviors for registration, configuration and general management of the agents. Send/receive messages can be implemented by calling basic methods using standard communication protocols and registering in several domains. External software can be integrated by the use of behavior abstraction, which enables the link with the OPC UA nodes along with the JADE agent messages [30].

D. IEDs and Hardware Components

The intelligent multi agent framework is implemented in a reconfigurable small scale power system available at Florida International University, Smart Grid Test Bed [31-34]. The platform consists of conventional and non-conventional generation units, transmission and load models, field sensors and actuators. Further information about the test bed can be obtained from above references.

The IEDs are located on system buses to enable monitoring, control and protection. The agent platform was implemented on a single personal computer, however since the information is accessible through the network, the computation can be easily distributed [38]. An off-the-shelf OPC UA server [33] was implemented to acquire IEC 61850 logical node measurements. An OPC UA client [35] was embedded in the Java platform to enable JADE to access mapped IEC 61850 measurements. The overview of the laboratory setup is shown in Fig. 5.

IV. Sample Use Case: DER Ancillary Service

A DER based autonomous ancillary service use case is demonstrated in real-time for validation of the proposed multi agent framework using the combination of IEC 61850 and FIPA standards. The IEEE guide 1547.3 defines DER interoperability issues by means of monitoring, information exchange, and control. Some use cases are demonstrated as business operations of the DERs and stakeholder entities with direct communication interactions [36].

Fig. 5 Agent platform and laboratory setup

This case study was adopted from IEEE 1547.3 guide to provide a prototype demonstration of the developed framework. The DER units can be utilized to provide ancillary services such as load regulation and reactive power support in distribution feeders. Especially in peak hours, the excessive energy demand may result in overloading of the distribution lines by drawing excessive current. This would result in thermal overheating and voltage drops beyond permissible limits on different parts of the feeder. Scheduled operation of DERs would provide a solution to relieve such overloading problems by contributing with either active or reactive power support [39]. According to [37]-[40], DER operators and the area electric power system operator (AESPO) interact with each other though messages. These two entities can be considered as intelligent agents with the following duties and attributes:

1) AESPO

It is the responsible entity for safe and reliable operation of the distribution power system. The complete utility grid model is the property of AESPO.

2) DER Operator

It is the main responsible entity for DER generation units. Monitoring, protection and control of the units are handled by DER operators.

AESPO and DER operator are the two entities that carry out the stated ancillary service mechanisms. The decentralized collaboration of AESPO and DER operators is based on an autonomous event-driven information exchange model, which requires implementation of agents featuring actuators, sensors, embedded intelligent decision making algorithms, and communication channels.

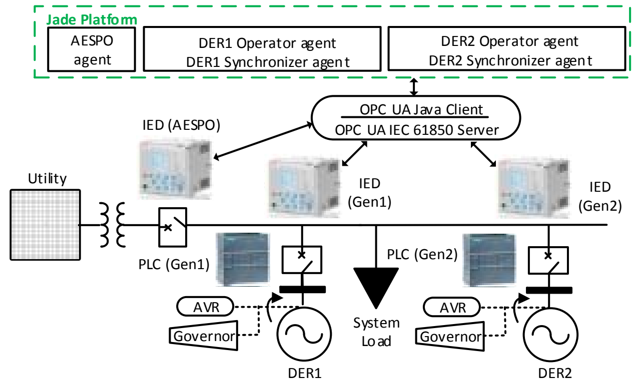

Fig. 6 IED deployment and agents

Fig. 6 illustrates the laboratory deployment of the multi agent framework, IEDs, PLCs, line models, loads, DERs, automatic voltage regulators (AVR) and governors.

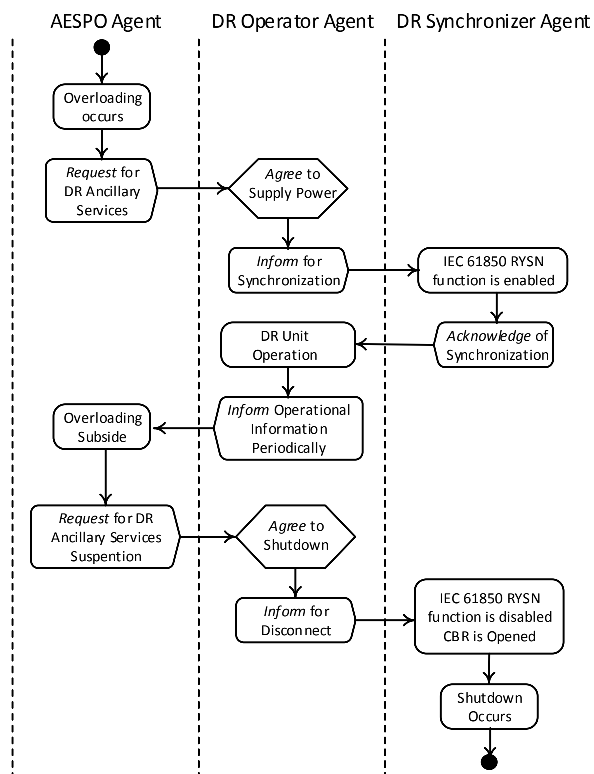

Fig. 7 Ancillary service use case UML flowchart

The cooperation agreement of the entities is established by sent/received messages from each parties in a certain form and an understandable content. This common or shared structured vocabulary is referred as the system ontology. Ontologies are constructed with a consistent relationship within an application domain. Abstraction is a way to express the real world objects with their characteristics, attributes and interaction with other entities. Prior to actual computer code implementation, unified modeling language (UML) tools are utilized to provide a meaningful abstract modeling of the emulated case. Event-driven sequencing outcome of the case presented in this paper is illustrated in Fig. 7. In this use case, AESPO agent and DER operator agents are defined in the JADE platform. The AESPO agent is intended to continuously check the critical current flow value from the beginning point of the feeder through the IEC 61850 current measurement (CMMXU) logical node.

When the current flow from the feeder reaches its critical value, the high-alarm node *LDO.CMMXU.HiAlm.stVal* of the function block becomes high. The AESPO agent is monitoring this value through the OPC UA client. According to embedded intelligent decision making algorithm an ancillary service support *Request* message is published to DER operator agents which are registered to the directory service (yellow pages). The yellow page is a service mechanism, in which an agent can find other agents providing the services it requires in order to achieve its goals. The directory facilitator (DF) is the agent that provides yellow page service to the agent platform. The AESPO agent periodically looks up available operators from the DF agent. A random availability function is defined for each DER operator to define whether to issue an *Agree* or *Reject* message in return. Fig. 8 shows the correspondence between the AESPO agent and two DERs.

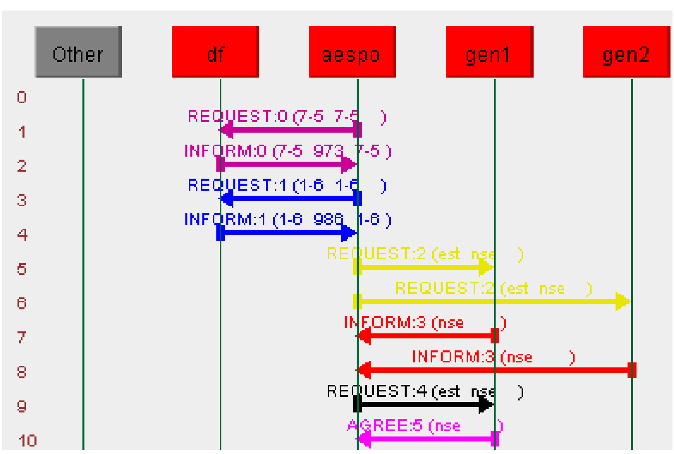

Fig. 8. Correspondence between JADE agents

If the DER operator agrees to provide ancillary service, it autonomously enables the DER synchronizer agent. The DER synchronizer agent is the IEC 61850 synchronism check (RSYN) logical node of the IED and it is not defined in JADE platform. The DER synchronizer agent continuously checks the condition across the circuit breaker from the bus and line parts of the power system and gives the permission to close the circuit breaker when the synchronization conditions are satisfied. The determination of the closing signal is defined according to frequency and phase angle difference. The monitored frequency and phase angle difference value is continuously read by PLC in order to adjust the governor speed. U_BUS and U_LINE are bus voltage and line voltage measurements, respectively. The synchronization status can be obtained from the function block by SYNC_INPRO (synchronization in progress) or SYNC_OK (in synchronism). LLDB (live line, dead bus), LLLB (live line, live bus), DLLB (dead line, live bus), DLDB (dead line, dead bus) outputs designate the health of the line and bus.

Fig.9 (a)-(b) shows the frequency and phase angle difference of the DER and AESPO. The figures cover 30 seconds of the synchronization process. From the 35th to 65th second, the generator output frequency decreased manually by decresing the applied torque to the generator shaft from the governor. At the 70th second, the utility and generator frequency match, thus the synchronizer switch is closed. At the 76th second, the applied torque to the generator shaft was increased to deliver more power to the system. Fig.9 (b) shows the phase angle difference between of AESPO and DER voltage. As synchronization occurs at the 70th second, the phase angle difference decreases to a value almost equal to zero. This clearly shows that the generator is synchronized to the utility.

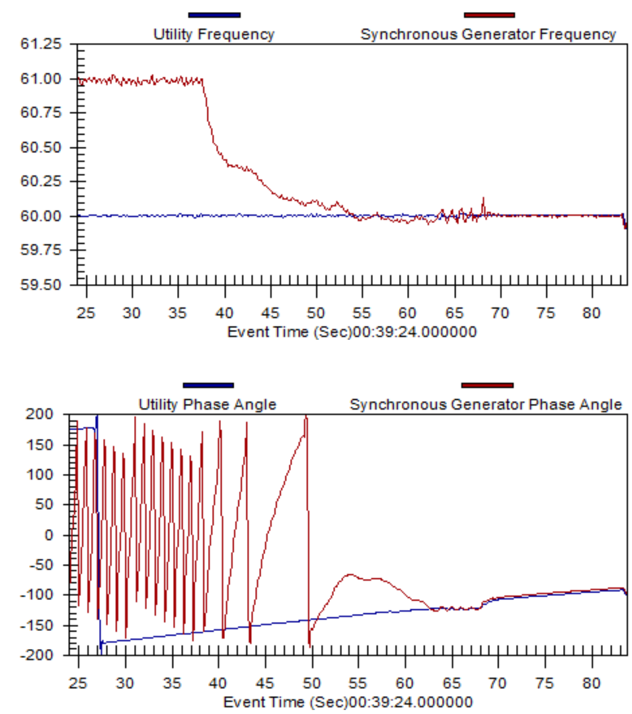

Fig. 9. (a) Frequency change (b) Phase angle difference

V. CONCLUSION

This paper presented a real-time implementation of a laboratory based intelligent multi agent framework using IEC 61850 and FIPA standards. The IEC 61850, OPC UA, JADE platforms and a hardware setup were introduced as a complete cyber-physical structure. Merging these multi agent legacy protocols proposes an enhanced interoperability framework for future smart grid deployments. Experimental results are given in order to validate the effectiveness of the proposed framework. The proposed framework is highly recommended for secondary and tertiary level intelligent multi agent based decentralized control schemes such as voltage/frequency regulation and economic issues in the power systems.

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