Multiagent-based decentralized operation of microgrids considering data interoperability

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Multiagent-Based Decentralized Operation of Microgrids Considering Data Interoperability

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***Abstract*—Transition from conventional power distribution to active distribution networks requires extensive integration of decentralized microgrid control capabilities with on-demand industrial data interoperability. This paper presents a decentralized hierarchical microgrid operation scheme with a multiagent framework using IEC 61850 and the foundation for intelligent physical agents (FIPA) standards. The conducted studies are mainly focused on secondary and tertiary control levels. Secondary control deals with the operational reliability of the microgrid with a decentralized remote interaction between distributed energy resources (DER) and microgrid operator. Tertiary level presents the aggregated operation of multiple microgrids aiming to enhance the reliability of the host grid with ancillary services. Experimental results are presented in a laboratory based test bed involving actual intelligent electronic devices (IED) and multiple microgrids.**

***Index Terms*—Microgrid, FIPA, smart grid, cloud, multiagent, IEC 61850, Jade, hierarchical control, OPC UA, decentralized control, interoperability**

I. INTRODUCTION

CENTRALIZED methods of operation are more susceptible to single point failures, where managing the vast number of data generated from the extensive deployment of smart devices becomes infeasible. Due to their inherent resilience, decentralized methods have drawn considerably more attention than centralized methods. Decentralized control approaches intend to provide autonomy for hierarchical control layers by enabling a bidirectional event-driven peer-to-peer communication structure, where central control schemes mainly rely on one way master-slave messaging interactions [1].

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 a local objective function. Multi-agent based schemes are widely applied to power system controls in literature; including self-healing, resilient grid automation [2]-[3] and power system protection [4]-[5]. Multiagent-based microgrid control draws considerably more attention than any other smart grid applications as one of the main assets of emerging active distribution network concept [6]. Multi-agent based hierarchical hybrid control for microgrid is proposed to maintain voltage and maximize economic benefit [7]. In [8] and [9], multi-agent based distributed energy resource (DER) management of microgrids are presented. Microgrid market operations are implemented in a simulation [10], in a real-time digital simulator [11] and in a laboratory-based hardware platform [12] using multi-agent based controls.

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Although many multiagent-based microgrid studies have been reported, none of the previous works address the industrial data interoperability, which is crucial for actual field deployment. Most of the works have been validated in simulation environments where data interoperability of the cyber-physical components have never been an issue. In reality, an agent requires to interact 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. 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 smart meters, phasor measurement units (PMU) [13], intelligent electronic devices (IED) and programmable logic controllers (PLC) [14]. The required interface is established through a combination of interoperable data and protocols.

Interoperability of the field devices with an agent based communication capability is one of the challenges to accomplish decentralized control of smart grid infrastructure. Attempts to extend IEC 61850 protocol with IEC 61850-7-420 for distributed energy resource (DER) control are promising, however, the smart grid concept covers extensive control, automation and protection applications such that a single standard cannot meet all the required forms of monitoring and information exchange [15]. Hierarchical control of the microgrids require interaction with utilities for dynamic management of the primary, secondary and tertiary control levels [16]. To achieve future microgrid decentralized control goals, advanced intelligent multiagent frameworks are required with the flexible ability to create tailor-made decentralized control schemes while following the power system 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 [17]. Java agent development framework (JADE) is a software framework to develop agents compliant with FIPA standards with flexible agent behavior methods [18]. The flexibility of the java environment facilitates tailor-made agent implementation. Taking the specific benefits of two major frameworks, this work intends to provide a flexible multi-agent framework for decentralized hierarchical control of microgrids merging the IEC 61850 and FIPA standards. The open connectivity unified architecture (OPC UA) is adopted as a middleware and a cloud data service is integrated to provide real-time information exchange though the internet to enhance the data availability for remote access points [19-23].

Briefly, the major contributions of this paper presents are: 1) a tailor-made flexible hybrid multi-agent framework for secondary and tertiary levels for hierarchical microgrid operation considering legacy power system data protocols explicitly IEC 61850 and FIPA standards; 2) the integration of the proposed framework with a cloud real-time data service to provide ubiquitous data interoperability and remote location data access; and 3) a unique laboratory-based cyber-physical infrastructure to validate the proposed framework.

The remainder of the paper is as follows. Section II gives an overview of the hierarchical control of microgrids. In Section III, the developed cyber-physical multiagent framework is explained in detail. Section IV demonstrates the hardware setup and the real-time experimental results of the secondary and tertiary level microgrid control experiments. The conclusion and discussion are stated in Section VI.

II. Hierarchical Microgrid Control

Hierarchical control of microgrids is a compromise between fully centralized and fully decentralized control schemes [24]. In literature, three distinct control levels are introduced according to control response speed and communication infrastructure requirements. Primary control level deals with output power control of each individual DER unit, which is based on local measurements and in general depending on the control method (e.g droop control), does not require remote decentralized communication. Hence, this control level is not one of the primary concerns of this paper.

Secondary control deals with the economical and operational reliability of the microgrids. Two distinct approaches can be implemented in this level: (i) centralized; and (ii) decentralized. Centralized methods are extensively covered in literature. Although this control method provides an opportunity to use advanced optimization tools, the major drawback of the centralized methods are the requirement of high communication capability with a powerful central controller thus being susceptible to single point, failure, which can easily compromise the system with a complete collapse. Agent based communication approaches are well-suited for decentralized controls in secondary level for cooperation inside the microgrid especially for stand-alone systems. Secondary control is achieved by DER units which are generally located in same microgrid, and are not widely dispersed, so long distance communication is not a major concern.

Tertiary control can be assumed as the interaction of multiple microgrids with a host grid. Aggregated cooperation of multiple microgrids enhances the reliability of the host grid with ancillary services such as voltage and frequency regulation. Since a vast amount of information is required for this highly complex system, decentralized methods are more favorable for this geographically dispersed system. Since controllers are located at remote location, advanced communication infrastructures are required such as cloud-based services.

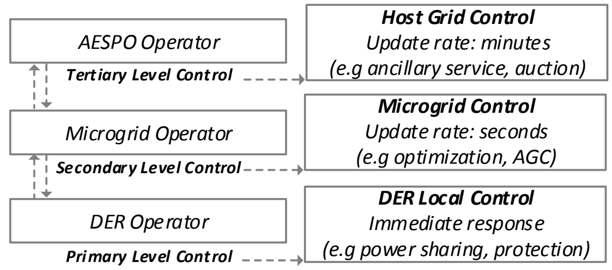

Fig.1. Hierarchical control of a microgrid

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 [25]. In this study, we adopted a model in which three control levels are defined hierarchically and linked to appropriate agents as shown in Fig.1: (i) area electric power system operator (AESPO); (ii) Microgrid operators; (iii) DER operators.

- *AESPO:* is the responsible entity for safe and reliable operation of the host grid. The complete utility grid model is the property of AESPO. Tertiary level controls are handled by interaction of AESPO and Microgrid Operators such as economic dispatch of the units and the auction process.
- *Microgrid Operator:* is the main responsible entity for monitoring, dispatch and control of the units inside the microgrid. Secondary controls are handled with interaction of Microgrid Operators and DER Operators such as optimization and automatic generation control (AGC).
- *DER Operator:* is the main responsible entity for individual DER generation units. Monitoring, protection and primary control of the units are handled by DER operators such as power sharing and protection.

III. Proposed Multi-Agent Framework

This section briefly explains the hardware and data information model of the proposed framework.

A. *IEC 61860 Framework*

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. Logical nodes (abstract data objects) are the main elements of the IEC 61850 object oriented virtual model, which consists of standardized data and data attributes. 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.

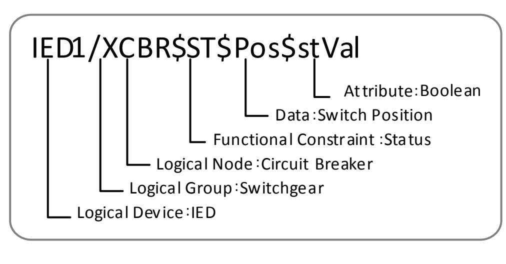

Fig.2. Object name of a circuit breaker position value

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), involving 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.2. shows a sample anatomy of an object name for a breaker position value.

B. FIPA Specifications and JADE Platform

Agent communication language (ACL) represents a communicative act or messages intended to perform some action, with precisely defined syntax and semantics. An agent is an interacting object with its own thread of control that operates autonomously. Fig.3. shows a representation of a message exchanged between interacting agents. 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 [26]. 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 a link with OPC UA nodes along with JADE agent messages [27].

C. OPC UA

OPC UA uses a framework based on client and server architecture, in which the server provides real-time data to clients. The OPC UA modeling is based on nodes and references between the nodes [28]. 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 a client and returns a result. The OPC UA address space is structured with objects containing only the node attributes.

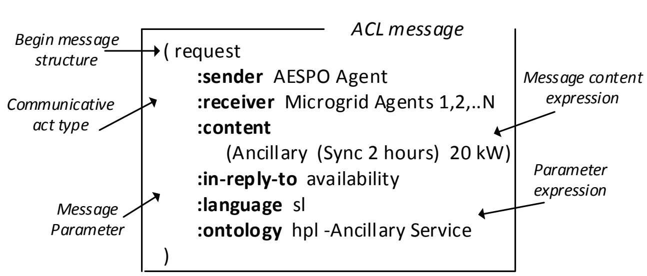

Fig.3. ACL message components

Fig. 4 Agent platform and laboratory setup

D. Physical Hardware-Based Microgrid

The proposed multi agent framework is implemented in a reconfigurable small scale power system available at Florida International University, Smart Grid Test Bed as shown in Fig.4 [29-30]. The IEDs are located on system buses to enable monitoring, control and protection. The agent platform is implemented on a single personal computer, yet the information is accessible through the network, the computation can be easily distributed. An off-the-shelf OPC UA server is implemented to acquire IEC 61850 logical node measurements. An OPC UA client is embedded in the Java platform to enable JADE to access mapped IEC 61850 measurements. The OPC UA data is published to the cloud-service, which can be utilized with remote OPC clients on the network.

IV. Experimental Results and Validation

This section introduces the real-time experiments to validate the proposed multiagent framework. A tertiary level control is demonstrated with an ancillary service for load regulation in the host grid feeder. Islanding detection [31-32] and automatic generation control (AGC) cases are demonstrated as secondary level control examples. The cooperation and agreement of the entities is established by sent/received messages from each parties in a certain form and an understandable content. The related event-driven sequence outcome of the proposed control is illustrated in Fig. 5. The case study starts with an overloading situation in the feeder, which results in the AESPO agent requesting for ancillary service as tertiary level control case.

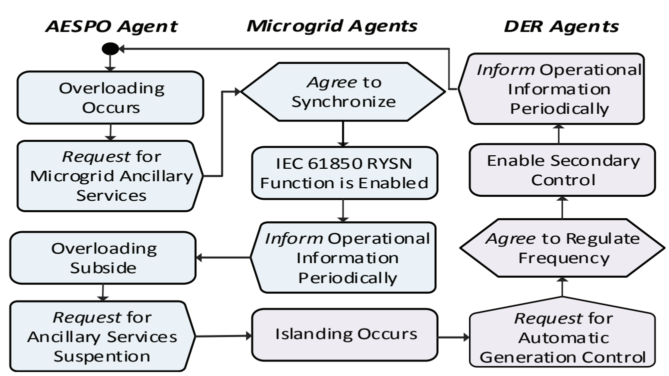

Fig. 5 Event-driven sequence of hierarchical microgrid operation

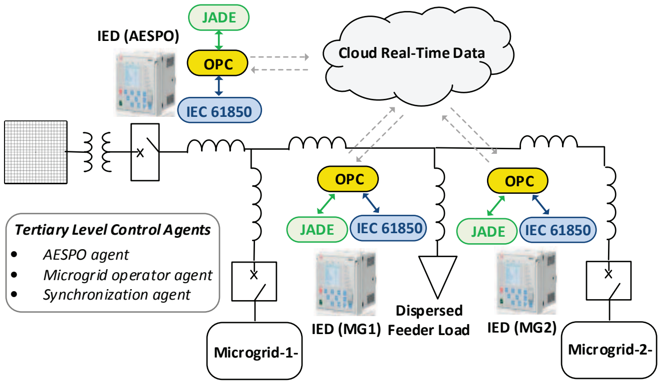

Fig. 6 Tertiary level control (ancillary service) cyber-physical setup

When overloading subsides, the AESPO agent requests suspension of ancillary service, which leads to microgrid islanding and accordingly frequency regulation with secondary control by AGC

A. *Tertiary Control (Ancillary Service)*

Microgrids can be utilized to provide ancillary services such as load regulation and reactive power support in distribution feeders. Especially during 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 microgrids would provide a solution to relieve such overloading problems by contributing with either active or reactive power support. Fig.6. shows the laboratory deployment of the multi agent framework with IEC 61850 IEDs, the OPC server, a Jade platform and a cloud interface for the tertiary control level. In this use case, the AESPO agent and microgrid 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 three-phase current measurement CMMXU function block, which is a logical node inherited from MMXU for metering and measurements [16]. 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 monitors this value through the OPC UA client. According to the embedded decision making algorithm, an ancillary service support *Request* message is published to the microgrid operator agents registered to the directory service (yellow pages). Yellow page is a service mechanism in Jade platform, 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 microgrid operator to define whether to issue an *Agree* or *Refuse* message in return. Fig. 7 shows the correspondence between the AESPO agent and two microgrid operator agents. If any of the microgrid operators agree to provide ancillary service, it enables the synchronizer agent.

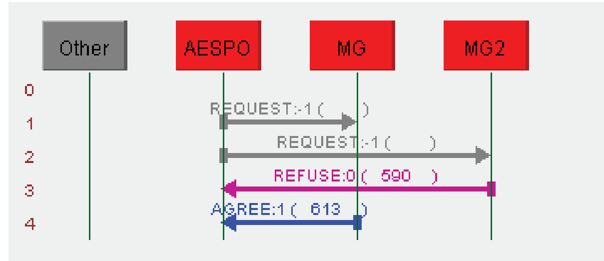

Fig. 7. Correspondence between AESPO agent and microgrid agents

The synchronizer agent is the IEC 61850 synchronism check (RSYN) logical node of the IED and it is not defined in JADE platform. The synchronizer agent continuously checks the condition across the circuit breaker from bus and line regions of the power system and gives the permission to close the circuit breaker when the synchronization conditions are satisfied, where f is the frequency, ϕ is phase angle difference, and T is the time duration (1). Synchronization permission and circuit breaker closing signal is subject to frequency, phase angle difference and voltage values from both sides of the circuit breaker. The monitored frequency and phase angle difference value is continuously read by a PLC in order to adjust the governor speed.

$$\begin{aligned} &T\left(\left|f_{host} - f_{microgrid}\right| \geq f_{threshold}\right) \geq T_{threshold} \\ &T\left(\left|\phi_{host} - \phi_{microgrid}\right| \geq \phi_{threshold}\right) \geq T_{threshold} \end{aligned} \tag{1}$$

Fig.8 (a)-(b) shows frequency and phase angle difference of AESPO and microgrid. The figures cover 30 seconds of the synchronization process. Initially, the microgrid is operating at 61 Hz. 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 AESPO and microgrid frequency match, thus the synchronizer switch is closed.

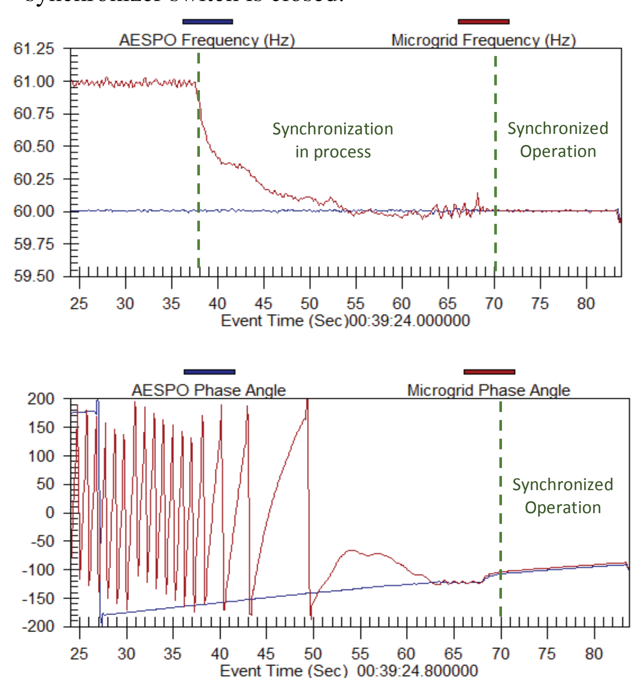

Fig. 8. (a) Frequency change (b) Phase angle difference

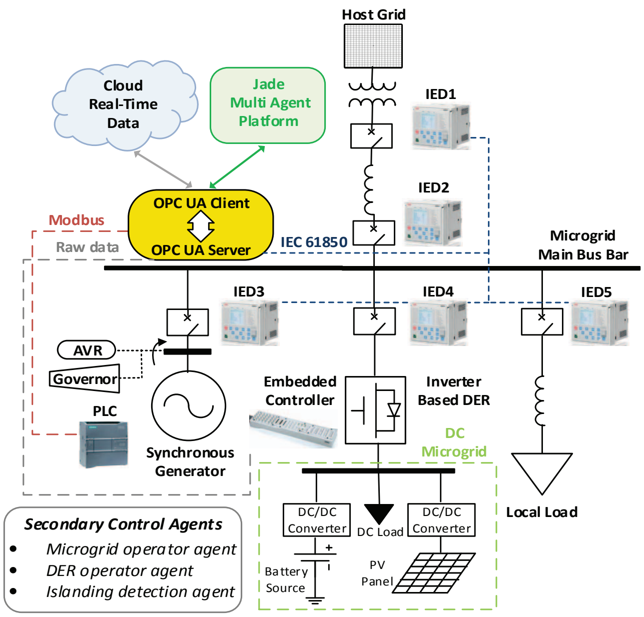

Fig. 9. Secondary level control (AGC) cyber-physical setup

At the 76th second, the applied torque to generator shaft is increased to deliver more power to the system. Fig.8 (b) shows the phase angle difference between AESPO and microgrid bus voltages. As synchronization occurs at the 70th second, the phase angle difference decreases to a value almost equal to zero. This clearly shows that the microgrid is synchronized to the utility.

B. Secondary Control (Islanding Detection and AGC)

Fig. 9 shows the implemented microgrid structure which involves conventional and renewable DERs. A microgrid can operate in grid-connected and islanded mode. In grid-connected operation mode, DER units operate in grid-feeding mode which exports constant active and reactive power.

Frequency and voltage regulation is handled by host grid. However, in islanded operation, a microgrid must be able to regulate internal frequency and voltage with a proper control. Droop control is the commonly accepted operation for power sharing among DERs in a microgrid. In the droop control scheme, the frequency can deviate from the nominal value based on loading conditions. Selecting one of the DER units to enable secondary control to restore the frequency to nominal value is a common practice in islanded operation.

In this case, when overloading subsides and the microgrid starts to draw power from the host grid, AESPO sends ancillary service suspension request to utility connected microgrids. Upon receiving request, microgrid gets disconnected from the host grid. Since prior to separation, the microgrid was importing power from the host grid, during the islanding situation, an immediate microgrid frequency dip is detected due to the power imbalance. The active power imbalance introduces frequency deviation in islanded microgrid (2), where H_{tot} is the total inertia, f_n is the nominal frequency, and f_s is the system frequency.

$$\Delta P(t) = (P_{gen}(t) - P_{load}(t)) = \frac{2H_{tot}}{f_n}\frac{df_s}{dt} \tag{2}$$

Microgrid operator and DER operator agents are defined in Jade platform and islanding detection agents are the FRPFRQ function block which inherits from PTOF logical node [16]. A consecutive islanding detection algorithm is used to enable islanding detection which senses under/over frequency setting initially, then the frequency gradient is compared to set value. When islanding is detected, the microgrid operator *Requests* DER operators to switch operation to droop control to enable accurate power sharing. Droop based primary control deviates the frequency from the nominal value according to the system loading conditions.

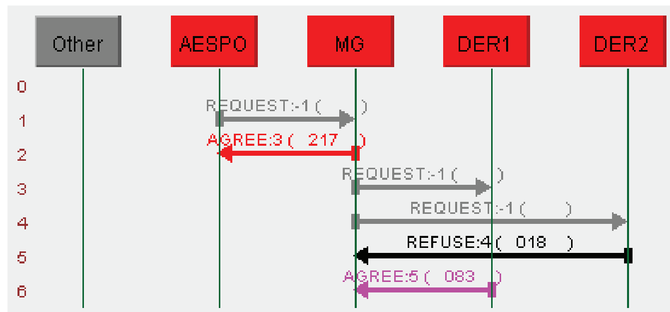

Fig. 10. Correspondence between microgrid and DER agents

AGC based secondary control is used to restore system frequency to nominal value. A common way to implement AGC in power systems is to implement a proportional-integral (PI) controller. An Area control error (ACE) in a power system is given as (3), where B is the frequency bias factor, ΔP_T is the deviation of active power balance in area, and ΔP_{AGC} is the control command to be sent to the governor. β_1 and β_2 are the PI control coefficients.

$$\begin{aligned} ACE &= \Delta P_T + B\Delta f \\ \Delta P_{AGC} &= -\beta_1 ACE - \beta_2 \int ACE dt \end{aligned} \tag{3}$$

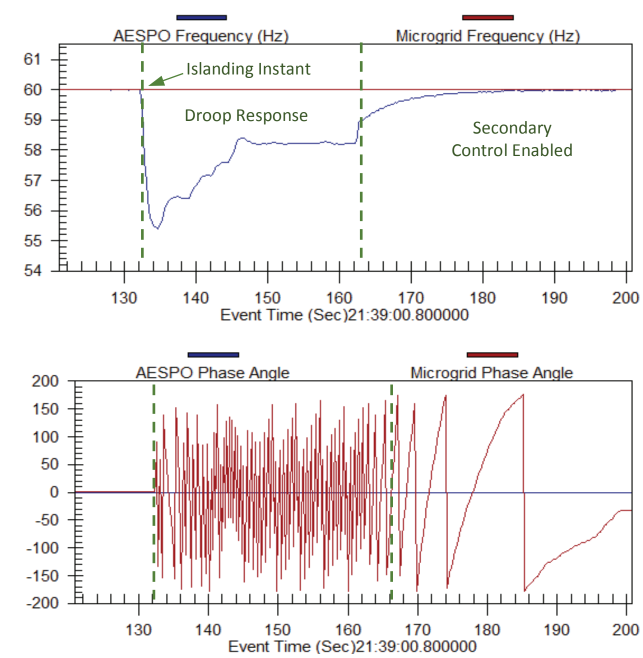

Fig. 11. (a) Frequency change (b) Phase angle difference

Microgrid operator agent requests DER operator agents to serve as frequency regulator unit to restore the system frequency to nominal level. Fig. 10 shows the correspondence microgrid operator agent and DER operator agents. In this case, inverter-based DER *Agrees* to enable AGC to restore the system frequency. Fig. 11 (a)-(b) shows frequency and phase angle difference of AESPO and microgrid during the secondary control process. From 100th to 130th second, the microgrid is operating in grid connected mode. When islanding detected at 130th second, the droop controller of the DERs are enabled. This results settling of the operation frequency to 58.5 Hz for the remainder of the operation in this loading level. At 170th secondary control is enabled by inverter-based DER to restore system frequency to nominal value of 60 Hz. The phase angle difference clearly shows the AESPO and microgrid are operating separately.

V. Conclusion

This study presents an industrial adaptation of agent technology to microgrids considering data interoperability. This work proposed an agent framework based on IEC 61850 and FIPA standards. The proposed framework is validated by real-time experiments with secondary and tertiary microgrid operations in a state-of-the-art smart grid laboratory setup.

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