Integration of IEC 61850 into a Distributed Energy Resources System in a Smart Green Building

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***Abstract*—A Distributed Energy Resources (DER) system, composed of distributed generation and storage units, has been proposed as a promising enhancement to the traditional power grids. One key challenge to implement a DER system, however, places on standardizing the communication network for seamless information exchange. As one approach, this paper focuses on integrating IEC 61850, which is an international unified standard for standardizing the communication network within a substation, into a DER system, using the UCLA SMERC building as test bed. To this end, we discuss a mathematical model of PV generation, present a representative demand profile, and develop a battery charging/discharging control algorithm. Moreover, we demonstrate a procedure to integrate IEC 61850 into the DER system step by step, with configuring the communication network and defining the data structure for the information exchange.**

I. Introduction

The traditional power generation such as coal and diesel has been experiencing energy crisis and confronting increasing concerns on environmental pollution as well as transmission loss. With the emergence of the smart grid concept, Distributed Energy Resources (DER), which accelerates the use of renewable generation such as solar and wind and provides the energy directly to local distribution grids, catches special attention. In this way, a DER system, composed of distributed generation and storage units, resolves the above-mentioned problems and has been proposed as a promising enhancement to the traditional power grids.

One key challenge to implement a DER system, however, places on standardizing the communication network for seamless information exchange. The lack of a common framework hinders its wide deployment in a real field. To overcome the challenge, international organizations make efforts to develop a standardized protocol. International Electrotechnical Commission (IEC) develops IEC 61850 to be such a international unified standard for standardizing the communication network within a substation [1]-[3]. While originally designed for substation automation, IEC 61850 has been applied to standardize the communication network within a DER system in the recent years. In particular, IEC 61850-7-420 describes the feasibility of the application into a DER system, which includes how to define a common format to describe the DER system, exchange the status information as well as map to the other communication protocols. Paper [4] and [5] talk about some existing research on the application. But, unfortunately, few previous studies have investigated the integration of IEC 61850 into a DER system in depth and thus the integration has been understood at an abstract level. To address the issue, this paper examines the integration with more precise and explicit definitions of the data structures for each component in the DER system and demonstrates its feasibility using a smart green building as testbed.

The objective of the paper is to implement a DER system using the UCLA SMERC building as test bed with the integration of IEC 61850, which is a real case study. We aim to develop the DER system that is composed of solar PV panels, battery storage units and various loads such as electric vehicles (EV), LED lightings and smart appliances [6]. In order to standardize the information exchange in the communication network, IEC 61850 is expected to be integrated into the DER system. The methods of modeling the system and integrating the standard that are described in the paper can be helpful for the implementation of similar DER systems using IEC 61850.

In the following, Section II describes the system architecture that includes the PV generation, demand profile and battery charging/discharging control algorithm in the DER system. In Section III, we demonstrate a procedure to integrate IEC 61850 into the DER system step by step, with configuring the communication network and defining the data structure for the information exchange. Section IV presents the results of implementation and integration. The conclusions and further work are given in Section V.

II. System Configuration

Fig 1 presents the system architecture of the UCLA SMERC building, which is a typical DER system test bed. The DER system is connected with the main grid through the point of isolating device. The device works as a switch, which can disconnect the DER system from the main grid when the unexpected failure happens. Below the 110 V AC bus, 5 kW solar PV panels are located at the roof of the building and accompanied by 10 kWh battery storage units. The loads include EVs, LED lightings and smart appliances, with total peak demand around 5 kW. In the following sections, we describe each component respectively.

A. PV Generation

Solar is one necessary renewable energy on the supply side of the DER system. We are currently installing real PV panels on the roof of the building, and yet, this version of the test bed implements a virtual simulated real-time panel that follows the same hardware specification of the real device. The simulation of PV generation includes specifying the

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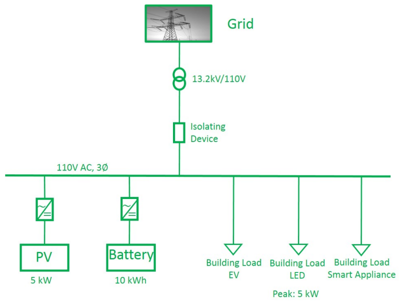

Figure 1. System Architecture of the DER system test bed

input data and modeling the solar generation. We obtain the hourly Global Horizontal Irradiation (GHI), Direct Normal Irradiation (DNI), and temperature (T) from a real-time online weather measurement station, as the input to trigger the simulation [7]. The calculation algorithm that models the solar generation is shown in Equation 1 and 2 for power generation (P), voltage (V) and current (I) [8].

$$P = \alpha(GHI + DNI) \times S \times \eta = VI \tag{1}$$

$$I = I_l - I_0 \times (e^{\frac{qV}{KT}} - 1) \tag{2}$$

In Equation 1, $\alpha = 0.3$ is the adjustment factor to model the solar radiation based on the hardware specification, $S = 19.904\ m^2$ is the area of 5 kW PV panels, $\eta = 16.5\%$ is the efficiency that transforms solar to electricity. In Equation 2, $I_l = 5.754$ A is the light-generated current, $I_0 = 1.919 \times 10^{-40}$ A is the saturation current, $q = 1.6 \times 10^{-19}$ Columbus is the elementary charge, $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant [9]. Fig 2 gives an example of 24-hour input data including GHI, DNI and T in the DER system using the UCLA SMERC building as test bed. The simulation results based on this input are shown in Section IV.

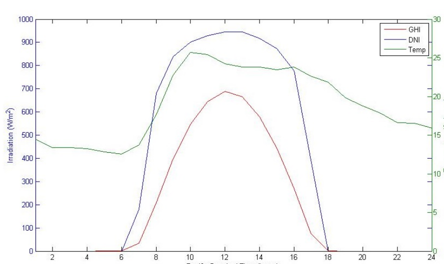

Figure 2. 24-hour solar data on Nov. 1st, 2013 in the DER system test bed

B. Demand Profile

The representative demand profile is generated from real data in the test bed. We use the Demand Response method in paper [10] to smooth the demand profile. As previously mentioned, the UCLA SMERC building contains three types of loads. Fig 3 gives an example of 24-hour demand profile in the DER system using the UCLA SMERC building as test bed. Type 1 Load is EV, shown as the purple line. Here we have opposite charging pattern in the building, compared to common residential households. The demand for charging the electricity in the building is high at daytime during 8 AM to 5 PM, while the demand for charging the electricity at residential households is high at the night after 8 PM. The reason is that the test bed is the office building so most customers charge their EVs when they are working at daytime. Type 2 Load is 200 LED lightings in the building that must be on during the office hour, shown as the green line. Type 3 Load is the smart appliances, e.g., refrigerator, shown as the red line. This type of load is energy efficient but it must be on for 24 hours. The blue line is the total demand that is the summation of the three loads.

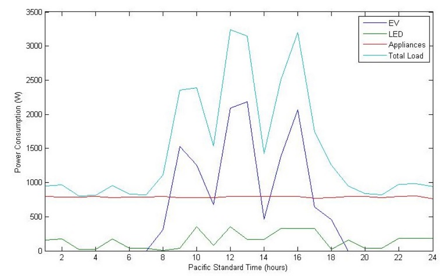

Figure 3. 24-hour demand profile on Nov. 1st, 2013 in the DER system test bed

C. Battery Control Algorithm

The DER system requires the assistance of battery storage due to the intermittency and uncertainty of the renewable energy. In paper [11], we introduce a battery model for an islanded microgrid. In this paper, we apply the similar model with minor improvement. Briefly, the Status of Charge (SOC) in the battery depends on the differences between the amounts of the supply and the demand at each time interval. Fig 4 summarizes the battery charging/discharging control algorithm in flowchart, where $S(t)$ is the generation at time t, $L(t)$ is the load at time t, $B = 10$ kWh is the capacity of battery, $B_I = B$ is the initial status of the battery, $\gamma_1 = 80\%$ is the charging efficiency which is the percentage of the amount of energy that is charged into the battery, $\gamma_2 = 80\%$ is the discharging efficiency which is the percentage of the amount of energy that is discharged from the battery, $b^- = 9$ kWh is the maximum SOC and $b_- = 1$ kWh is the minimum SOC.

III. Integration of IEC 61850

A. Integration Procedure

IEC 61850 is an international unified standard that aims to standardize the communications within the substation automation system. Table 1 lists the contains of the standard for each part [12]. As we discussed, IEC 61850 can be applied to standardize the communication network within the DER system in the recent years. In the current market, though many big enterprises that manufacture the distributed generation can provide their own Application Programming Interfaces (API), many small enterprises do not want to implement their

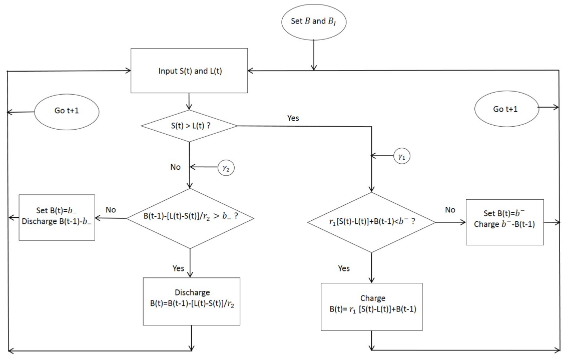

Figure 4. Flowchart of battery control algorithm in the DER system test bed

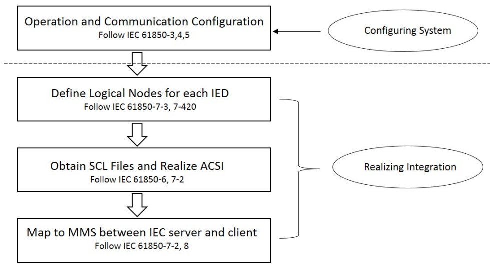

Figure 5. Procedure to integrate IEC 61850 into the DER system test bed

own due to limited time and cost. In addition, there is need to translate each API when the components from different enterprises communicate with each other in the DER system. IEC 61850 is designed to obtain the efficient interoperability among different APIs. No matter what protocols they previously used, now they can adopt one IEC 61850 standard and seamlessly integrate into one common communication network. That is the reason why IEC 61850 was developed.

Table I
CONTAINS OF IEC 61850

Part #	Title
IEC 61850-1	Introduction of Overview
IEC 61850-2	Glossary of Terms
IEC 61850-3	General Requirement
IEC 61850-4	System and Project Management
IEC 61850-5	Communication Requirements
IEC 61850-6	Substation Configuration Language
IEC 61850-7-2	Abstract Communication Service Interface
IEC 61850-7-3	Common Data Classes
IEC 61850-7-420	Logical Nodes in DER system
IEC 61850-8	Mapping to MMS and ISO/IEC
IEC 61850-9	Mapping to Sample Values
IEC 61850-10	Conformance Testing

Fig 5 shows the procedure to integrate the standard into the DER system using the UCLA SMERC building as test bed. The details are explained in Section III-B and III-C. We first need to configure the DER system that follows IEC 61850 requirements. This step includes operation and communication configurations respectively, according to IEC 61850-3, 4, 5. The second step is to specify the Intelligent Electronic Devices (IED) and define the logical nodes for each logical device in the DER system, according to IEC 61850-7-3, 7-420. By these definitions, we can develop the files which are used to exchange information in the DER system using Substation Configuration Language (SCL), according to IEC 61850-6. Meanwhile, the SCL files are exchanged in the Abstract Communication Service Interface (ACSI) between IEDs and server, according to IEC 61850-7-2. Finally, An IEC 61850 server is deployed to communicate with IEC 61850 client. According to IEC 61850-7-2 and 8, the communication between the IEC 61850 server and client is realized via Manufacturing Message Specification, ISO 9506 (MMS). The last step is still in progress and we discuss it in Section V.

B. System Configuration

1) Operation Configuration: Fig 6 presents the operation configuration of the DER system [12]. It is similar to Fig 1 but it displays the system using IEC 61850 format. According to IEC 61850-5, the DER system can be described by classifying different levels. From the figure, one substation level is classified because the DER system can be one complete system. Since there is one transformer that transforms the power voltage from 13.2 kV to 110 V, two voltage levels are classified. Five bay levels are classified because there are five core components in the DER system. Table II makes the summary of the classification with representation and description.

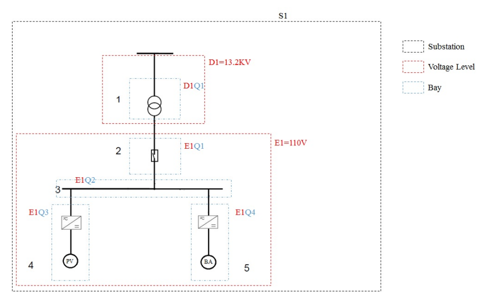

Figure 6. Operation configuration of the DER system test bed

Table II
SUMMARY OF THE OPERATION CONFIGURATION OF THE DER SYSTEM TEST BED

Classification	Representation	Description
Substation Level	S1	The DER system
Voltage Level	D1	13.2 kV level
	E1	110 V level
Bay Level	D1Q1	Transformer
	E1Q1	Isolating Device
	E1Q2	Bus
	E1Q3	PV system
	E1Q4	Battery system

2) Communication Configuration: Fig 7 presents the communication configuration of the DER system that follows IEC 61850 requirements. It uses Fig 6 as the base and adds the communication part. From the figure, we can specify two IEDs: PV controller and Battery controller. In the communication network which is standardized by IEC 61850, an IED works as an intermediate that receives the status information from real device and transmits to the IEC 61850 server via ACSI using SCL files. The server processes the data and communicates with IEC 61850 client such as control center via MMS.

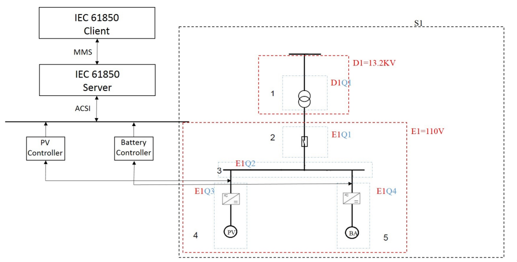

Figure 7. Communication configuration of the DER system test bed

C. Realization of Integration

An IED is described using a specific hierarchy common data class (CDC). The most important part in specifying the CDC for each IED is to define the logical nodes. According to IEC 61850-7-420, we define the logical nodes for PV IED and Battery IED in Table III and IV. For PV IED, we specify four logical nodes: DPVM is PV module characteristics, DPVA is PV array characteristics, MMET is meteorological measurement and MMXU is measuring and metering. For Battery IED, we specify two logical nodes: ZBAT is battery discharging system and ZBTC is battery charging system.

Table III
LOGICAL NODES OF PV IED

Logical Device	PV	
Data object name	CDC	Explanation
DPVM		
MaxMdulV	ASG	Module voltage at max power point, 41 Vdc
MaxMdulA	ASG	Module current at max power point, 5.25 Adc
MdulOpnCctV	ASG	Module open circuit voltage, 47.7 Vdc
MdulSrtCctA	ASG	Module short circuit current, 5.75 A dc
DPVA		
MdulCnt	ING	Number of modules per string, 8
ArrArea	ASG	Array Area, 19.904 m^2
Tilt	ASG	Fixed tilt, 20°
MMET		
GHI	MV	Global Horizontal Irradiation
DNI	MV	Direct Normal Irradiation
Temp	MV	Temperature
MMXU		
Power	MV	Array power output
Voltage	MV	Array voltage
Current	MV	Array current

IV. RESULTS

A. PV and Battery Simulation

Fig 8 shows the simulation results of 24-hour supply, demand and SOC in the DER system on Nov. 1st, 2013. The red line shows the supply generated by PV panels. We can see that it follows the same trend as GHI and DNI in Fig 2. The purple line shows the demand which is the summation of the three loads from EVs, LED lightings and smart appliances in

Table IV
LOGICAL NODES OF BATTERY IED

Logical Device	Battery	
Data object name	CDC	Explanation
ZBAT		
BatSt	SPS	Battery system status
BatTyp	ENG	Type of battery, 1: Lead-acid
DisChaRte	ASG	Discharge efficiency, 80%
MinBatSt	ASG	Minimum battery discharging status, 9 kWh
ChaSOC	MV	State of Charge
ZBTC		
ChaRte	ASG	Charge efficiency, 80%
MaxBatSt	ASG	Maximum battery charging status, 1 kWh
DisSOC	MV	State of Discharge

Fig 3. The green line shows the SOC in the battery which is calculated by the control algorithm in Fig 4. In Fig 8, the peak supply is 2680 W while the peak demand is 3238 W. After 4 PM, the SOC in the battery reaches its minimum state and cannot provide energy to the demands when the solar becomes insufficient.

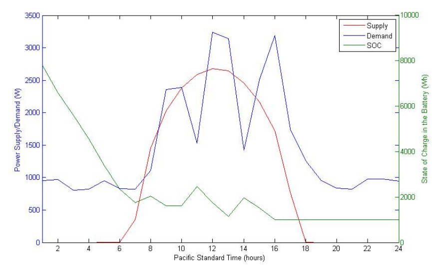

Figure 8. Simulated power supply, demand and SOC on Nov. 1st, 2013 in the DER system test bed

Fig 9 shows the simulation results of 24-hour voltage and current in the PV panels. We can see that the voltage keeps the same trend as the power while the current keeps the opposite trend because the power, voltage and current need to keep the relationship in Equation 1.

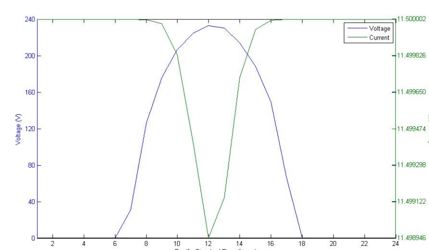

Figure 9. Simulated voltage and current on Nov. 1st, 2013 in the DER system test bed

B. Integration of IEC 61850

As we discussed in Section III-A and III-C, the most important part of the realization of integration is to develop and deliver the SCL files that are used to exchange information. These files contain the descriptions of the DER system, the definitions of CDCs for each IED and real-time status information that is used to exchange, following the requirements and formats specified in IEC 61850. Fig 10 and Fig 11 are two examples of the SCL files which show the descriptions of the logical nodes in PV IED and Battery IED and translate the information in Table III and Table IV in IEC 61850 formats, respectively.

```
<DataSet name="PV model characteristic">
        <FCDA ldInst="C1" prefix="" lnClass="DPVM" lnInst="1" doName="MaxMdulV" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="DPVM" lnInst="2" doName="MaxMdulA" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="DPVM" lnInst="3" doName="MdulOpnCctV" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="DPVM" lnInst="4" doName="MdulSrtCctA" fc=""/>
</DataSet>
<DataSet name="PV array characteristic">
        <FCDA ldInst="C1" prefix="" lnClass="DPVA" lnInst="1" doName="MdulCnt" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="DPVA" lnInst="2" doName="ArrArea" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="DPVA" lnInst="3" doName="Tilt" fc=""/>

</DataSet>
<DataSet name="Meteorological Measurements">
        <FCDA ldInst="C1" prefix="" lnClass="MMET" lnInst="1" doName="GHI" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="MMET" lnInst="2" doName="DNI" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="MMET" lnInst="3" doName="Temp" fc=""/>
 </DataSet>
 <DataSet name="Measuring and Metering">
        <FCDA ldInst="C1" prefix="" lnClass="MMXU" lnInst="1" doName="Power" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="MMXU" lnInst="2" doName="Voltage" fc=""/>
        <FCDA ldInst="C1" prefix="" lnClass="MMXU" lnInst="3" doName="Current" fc=""/>
</DataSet>
```

Figure 10. Example of SCL file in the DER system test bed: PV data object names

```
<DataSet name="Battery discharging system">
     <FCDA ldInst="C1" prefix="" lnClass="ZBAT" lnInst="1" doName="BatSt" fc=""/>
     <FCDA ldInst="C1" prefix="" lnClass="ZBAT" lnInst="2" doName="BatTyp" fc=""/>
     <FCDA ldInst="C1" prefix="" lnClass="ZBAT" lnInst="3" doName="DisChaRte" fc=""/>
.ass="ZBAT" lnInst="3" doName="MinBatSt" fc=""/>
     <FCDA ldInst="C1" prefix="" lnClass="ZBAT" lnInst="3" doName="ChaSOC" fc=""/>
</DataSet>
<DataSet name="Battery charging system">
     <FCDA ldInst="C1" prefix="" lnClass="ZBTC" lnInst="1" doName="ChaRte" fc=""/>
     <FCDA ldInst="C1" prefix="" lnClass="ZBTC" lnInst="2" doName="MaxBatSt" fc=""/>
     <FCDA ldInst="C1" prefix="" lnClass="ZBTC" lnInst="3" doName="DisSOC" fc=""/>
</DataSet>
```

Figure 11. Example of SCL file in the DER system test bed: Battery data object names

Figure 12 is an example of the SCL file which presents the status information of one data object name MMXU for PV IED, i.e., power, voltage and current. Figure 13 is an example of the SCL file which presents the status information of one data object name ZBTC for Battery IED, i.e., charging efficiency, maximum SOC and discharging SOC.

```
<LN inst="1" lnClass="MMXU" lnType="">
        <DOI name="Measuring and Metering">
                <DAI name="Power" valKind="Conf">
                        <Val>...</Val>
                </DAI>
        </DOI>
</LN>
<LN inst="2" lnClass="MMXU" lnType="">
        <DOI name="Measuring and Metering">
                <DAI name="Voltage" valKind="Conf">
                        <Val>...</Val>
                </DAI>
        </DOI>
</LN>
<LN inst="3" lnClass="MMXU" lnType="">
        <DOI name="Measuring and Metering">
                <DAI name="Current" valKind="Conf">
                        <Val>...</Val>
                </DAI>
        </DOI>
 </LN>
```

Figure 12. Example of SCL file in the DER system test bed: status information of MMXU in PV IED

```
<LN inst="1" lnClass="ZBTC" lnType="">
     <DOI name="Battery charging system">
          <DAI name="ChaRte" valKind="Conf">
                 <Val>0.8</Val>
          </DAI>
     </DOI>
</LN>
<LN inst="2" lnClass="ZBTC" lnType="">
     <DOI name="Battery charging system">
          <DAI name="MaxBatSt" valKind="Conf">
                 <Val>1</Val>
          </DAI>
     </DOI>
</LN>
<LN inst="3" lnClass="ZBTC" lnType="">
     <DOI name="Battery charging system">
          <DAI name="DisSOC" valKind="Conf">
                 <Val>...</Val>
          </DAI>
     </DOI>
</LN>
```

Figure 13. Example of SCL file in the DER system test bed: status information of ZBTC in Battery IED

V. Conclusions and Further Work

Throughout the paper, we implement a DER system by instructing solar PV panels, battery storage units and various loads such as EVs, LED lightings and smart appliances, in the UCLA SMERC building. We first discuss a mathematical model of the PV generation, present a representative demand profile and develop a battery charging/discharging control algorithm. The simulation results in Section IV-A depict how the DER system operates by balancing supply and demand. IEC 61850 is integrated in the communication network within the DER system through three steps: configuring the operation and communication requirements; specifying the data structure; and presenting the examples of the SCL files. The results in Section IV-B show the progress of the implementation and the integration of IEC 61850.

In the future, we will enhance our test bed by completing our implementation of 5 kW solar PV panels and 10 kWh battery storage units and conducting advanced experiments. We will also develop demand side management in the DER system. Another future work includes development of the IEC 61850 server and client via MMS protocol by following IEC 61850-8.

Acknowledgement

This work is supported by Korean Institute of Energy Research with grant number of 20112310. The authors would like to thank Na Li from Laboratory for Information and Decision Systems, Massachusetts Institute of Technology and Xiaorong Xie from Electrical Engineering, Tsinghua University for help on system modeling.

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