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Operation of battery energy storage system using extensional information model based on IEC 61850 for micro-grids

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Abstract: With increased penetration of energy storage system in micro-grids, rapid and standardised information exchange is becoming essential for secure and reliable operation of energy storage system. This study presents an extensional information model for battery energy storage system (BESS) in micro-grid, which is based on the communication standards of the International Electrotechnical Commission (IEC) 61850. The implementation framework for BESS operation based on the extensional information model is proposed in detail; and the actual BESS operation tests are performed through an intelligent electronic device and a micro-grid test system. The experimental results show that the proposed BESS extensional information model and the implementation framework for BESS operation are available, which demonstrates an effective solution for flexible operation of BESS.

1 Introduction

As important distributed energy resource (DER) in micro-grid, the energy storage devices typically include battery, super-capacitor, flywheel, etc. [1, 2]. They may be put into operation or cut off frequently due to comprehensive dispatching or random system power fluctuations, so the energy storage devices should realise the plug-and-play concept [3]. Besides, they need to provide customers with reliable power supply in the micro-grid autonomous mode [4], to participate in optimal management in the micro-grid grid-connected mode [5], or to realise the stable transition between the modes [6]. Therefore, it is necessary to build standardised and flexible information communication architecture for the coordinated control and optimal dispatching of energy storage devices in different operation modes.

IEC 61850 is the international standard for information exchange in substation automation, large hydro plants, and DERs. It provides the basic communication structure for the substation and the feeder equipment, covering the principles, the abstract communication service interface (ACSI), the common data classes (CDC), and the compatible logical node (LN) [7, 8]. An open framework that can provide the robust solution for large-scale DERs integration and control is a key issue in micro-grid. Some approaches are proposed to solve this problem using IEC 61850, such as using application modelling based on event-driven information services for optimised control [9], multi-level hierarchical automation system [10], multifunction IEC 61850 process bus [11], and multi-agent automation architecture based on the IEC 61850 intelligent LNs [12]. Some DER controllers with serial links can exchange data with an IEC 61850 communication network using the developed communication gateway [13].

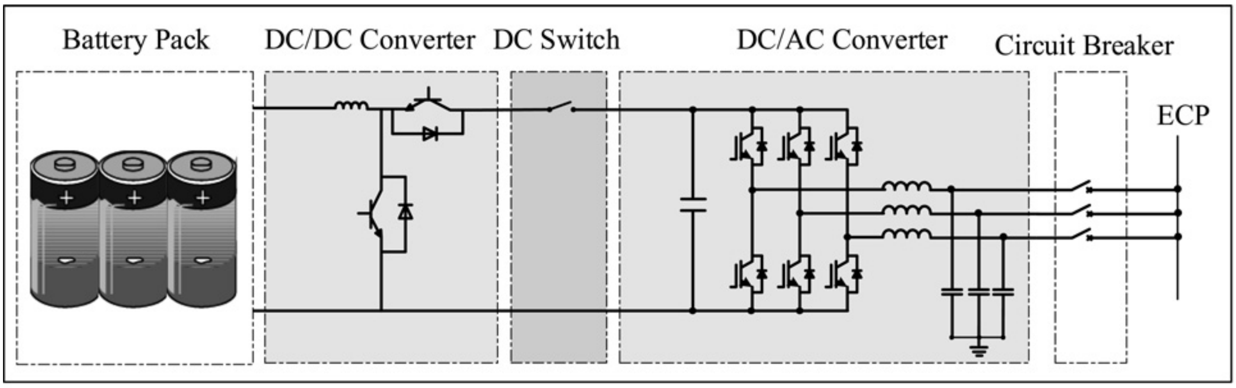
Data modelling is the foundation of the IEC 61850-based system integration. The LNs for the reciprocating engine model, the fuel cell model, and the PV panel model have been provided [14]. Some extensions for other DER information models such as wind turbines (WTs) and electric vehicles have also been addressed [15–17]. There is a lot of work addressing IEC 61850-based modelling, even energy storage system. IEC/TR 61850-90-7 describes the functions for power converter-based DER systems and provides IEC 61850 object models of inverters for energy storage systems [18]. Draft IEC/TR 61850-90-8 discusses IEC 61850 object models for electrical mobility, and Draft IEC/TR 61850-90-9 (PWI) focuses on using of IEC 61850 for electrical storage systems [19]. IEC 61850-7-420 provides ZBAT class for battery pack, ZBTC class for DC/DC converter, and ZINV class for DC/AC converter [14].

These works provide the general reference and principle for data modelling and system integration of energy storage system. However, energy storage system in micro-grid needs to realise some special applications due to the flexible operation of micro-grid, and its controllable power converters do not meet all requirements with the current IEC 61850 object models. In other words, the object models for controllable power converters of energy storage system in micro-grid should be extended, according to the requirements of especial applications.

To achieve the coordinated control and optimal dispatching of battery energy storage system (BESS) in micro-grid based on its typical applications, using the standardised and flexible information communication architecture, this paper contributes to BESS extensional information model for micro-grid, particularly proposing an implementation framework, to realise flexible operation of BESS based on the model in micro-grid according to the requirements of specific applications, and to solve the specific problems in actual applications of BESS, and to provide valuable references for rolling revision of IEC 61850 standards and technical reports. The implementation framework for BESS operation including information modelling, integration configuration, and information exchange between the BESS intelligent electronic device (IED) and micro-grid supervisory control and data acquisition system (SCADA) or energy management system (EMS) are further presented. The micro-grid test system and BESS IED are developed, and then BESS information exchange and operation tests are performed to illustrate the availability of BESS extensional information model and the implementation framework for BESS operation.

2 Methodology of BESS information modelling, integration and operation

The typically structure of BESS is shown in Fig. 1*a*. BESS is often connected to a micro-grid through the electrical connection point (ECP), and typically consists of a battery pack, power converters, and ancillary devices. The battery pack provides chemical energy



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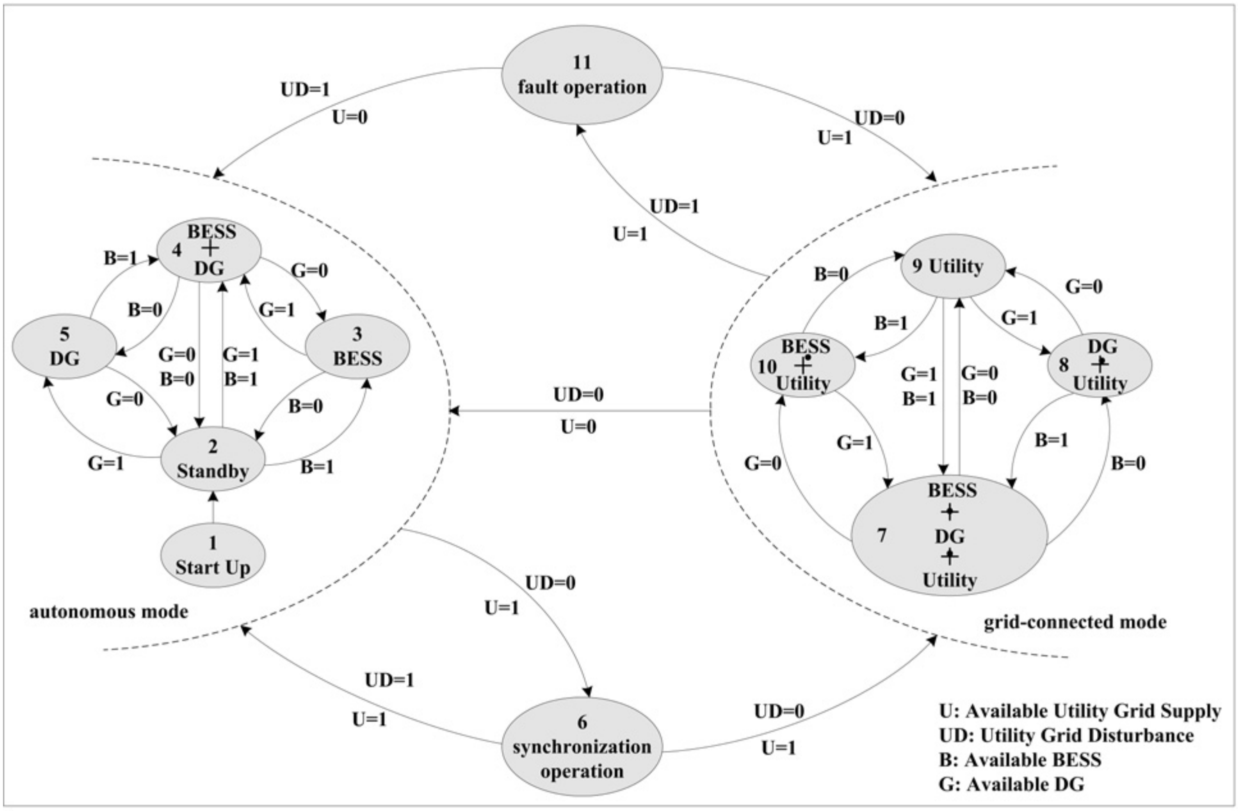


b

Fig. 1 *BESS in micro-grid*

a Schematic diagram of BESS
b Micro-grid operation states

as the primary energy resources. The power converters (typically, DC/AC converter, and DC/DC converter) are responsible for conversion of the primary energy into electricity and power flow adjustment as well as the transition between operation modes according to the system dispatching orders or the local operation strategies. The ancillary devices (typically, battery management system, and breakers) are responsible for the power transmission, faults protection, and operation monitoring.

Micro-grid has flexible system structure covering multiple components such as BESS, combined heat and power system, wind power system, and photovoltaic system. It has diverse applications and functions, for example, system startup, stability control, and optimal dispatching. Accordingly, micro-grid has flexible operation modes. The operation states of micro-grid are diverse and complicated as shown in Fig. 1*b*. When BESS is integrated into micro-grid, it should meet the following requirements:

2.1 Plug-and-play

Characteristics of BESS devices can be automatically identified by micro-grid EMS/SCADA when BESS is integrated, and its operation functions, such as monitoring, control, and setting can be configured by micro-grid EMS/SCADA.

2.2 Multiple operation strategies

BESS could participate in active/reactive power dispatching in the micro-grid grid-connected mode, or adaptive adjustment under multiple BESS operation, or voltage and frequency support in the micro-grid autonomous mode to provide the uninterrupted power supply. In addition, voltage and frequency support is also of high importance for the micro-grid grid-connected mode.

2.3 Operation strategies conversion

BESS needs to adopt different strategies according to the operation states in the micro-grid grid-connected mode or autonomous mode. In addition, BESS needs to change the strategies that are suitable for micro-grid operation modes conversion even during the fault operation and synchronisation operation, and ensure micro-grid reliable operation under various conditions.

Currently there are some valuable methodologies for IEC61850-based systems, mainly revolving around the updated information model and functional testing. The former usually proposes LN class for systems and equipment based on the requirements analysis of its application [16, 20]. The latter generally consists of building a test architecture, developing the hardware and software infrastructures, and tests scenarios verification [21–23]. For the presented requirements of BESS operation for micro-grid, multiple operation strategies can be satisfied by extending the corresponding information model, then plug-and-play and operation strategies conversion require the cooperation of micro-grid EMS/SCADA and BESS IED. Considering the aforementioned aspects for implementing BESS operation with IEC 61850, the proposed methodology in this paper is shown in Fig. 2.

The detailed requirements of BESS information model for micro-grids can be identified through the requirement analysis under typical BESS applications. Based on the proposed requirements of BESS information model, the object-oriented (OO) data modelling methodology is used to build BESS extensional information model, and then the required file for BESS IED can be obtained based on the extensional information model through the specific model configuration procedures according to IEC 61850-6. Meanwhile, functional modules of BESS IED and micro-grid EMS/SCADA can be designed based on the requirements of BESS applications. Further, BESS operation tests can be performed through the test system and information exchange implementation procedures.

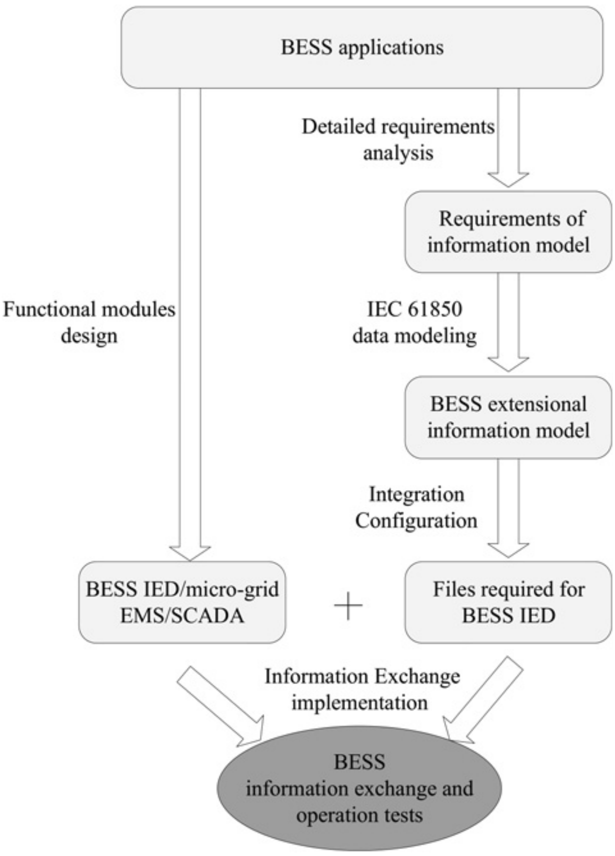


Fig. 2 *Methodology of BESS operation based on IEC 61850 for micro-grids*

3 Detailed requirements of BESS information model

3.1 Requirement analysis for information model of DC/DC converter

The typical power circuit and operation strategies of BESS DC/DC converter for micro-grid are shown in Fig. 3*a* (i_L is the inductor current, $V_{\rm dc}$ is the output voltage, and $V_{\rm dc\_ref}$ is the output voltage reference value).

The data object (DO) of ZBTC class specified by IEC 61850-7-420 reflects the information required for remote monitoring and control of critical DC/DC converter. *ZBTC.BatChaSt* reflects battery charger charging mode status. *ZBTC.BatChaTyp*, *ZBTC.ChaCrv*, *ZBTC.BatChaPwr*, and *ZBTC.BatChaMod* are respectively used to set battery charger type, charge curve, battery charging power required, and battery charger mode. *ZBTC.ChaV* and *ZBTC.ChaA* obtain the charging voltage and charging current, respectively [14].

As shown in Fig. 3*a*, $V_{\rm dc\_ref}$, $V_{\rm dc}$, and i_L are required, however, the existing Dos – *ZBTC.ChaV* and *ZBTC.ChaA* are usually used to represent battery pack charging voltage and total charging current from DC/AC converter, respectively [14]. In other words, $V_{\rm dc\_ref}$, $V_{\rm dc}$, and i_L should be represented by other DOs.

Considering the protection for the power circuit, the circuit voltages and currents should be limited. In addition, some operation information about the local/remote mode and alarm/fault is required by BESS IED or micro-grid EMS/SCADA. However, these requirements cannot be satisfied using the existing DOs in ZBTC class.

3.2 Requirement analysis for information model of DC/AC converter

The typical power circuit of BESS DC/AC converter for micro-grid is shown in Fig. 3*b* (L is the filter inductance, C is the filter capacitance, V_{abc} is the output voltages of DC/AC converter, i'_{abc} is the three-phase filter inductor currents, v_{abc} is the three-phase filter capacitor voltages, i_{abc} is the three-phase grid-connected currents, and e_{abc} is the three-phase ECP voltages).

The typical operation strategies of BESS DC/AC converter for micro-grid are shown in Fig. 3*c* ($P_{\rm out}$ is the actual active power output, $P_{\rm ref}$ is the output active power set-point, $Q_{\rm out}$ is the actual reactive power output, $Q_{\rm ref}$ is the output reactive power set-point, $V_{\rm ref}$ is the AC voltage set-point, and $f_{\rm ref}$ is the AC frequency set-point).

The ZINV class provided by IEC 61850-7-420 covers the universal characteristics of the inverter, which converts DC to AC. *ZINV.WRtg* and *ZINV.VarRtg* represent the maximum power rating and maximum Var rating, respectively. *ZINV.GridModSt* and *ZINV.GridMod* reflect the current- and power system connect modes to the power grid, respectively. *ZINV.OutWSet*, *ZINV.OutVar*, *ZINV.SetOutPF*, and *ZINV.SetOutHzSet* are used to set output power set-point, output reactive power set-point, power factor set-point as angle, and frequency set-point, respectively. *ZINV.HeatSinkTmp*, *ZINV.EnclTmp*, and *ZINV.AmbAirTemp* obtain the measured values of temperatures [14].

3.2.1 Active/reactive power (PQ) operation strategy: Due to the small system inertia of micro-grid compared to the utility grid, BESS should participate in active/reactive power dispatching to mitigate micro-grid power fluctuations and enhance the system inertia. In addition, BESS can also realise micro-grid multi-objective optimal operation through energy management in the micro-grid grid-connected mode. This requirement can be satisfied based on the PQ operation strategy as shown in Fig. 3*c*.

For the *PQ* operation strategy, i'_{abc}, v_{abc}, i_{abc}, and e_{abc} are required. $P_{\rm ref}$, $Q_{\rm ref}$, $P_{\rm out}$, and $Q_{\rm out}$ are also needful. The existing settings DOs – *ZINV.OutWSet* and *ZINV.OutVar* can be used to set $P_{\rm ref}$ and $Q_{\rm ref}$, respectively [14]. Then $P_{\rm out}$ and $Q_{\rm out}$ can be obtained through the active/reactive power calculation unit based on i_{abc} and e_{abc}, respectively. However, there is lack of measured values DOs for representing i'_{abc}, v_{abc}, i_{abc}, and e_{abc}.

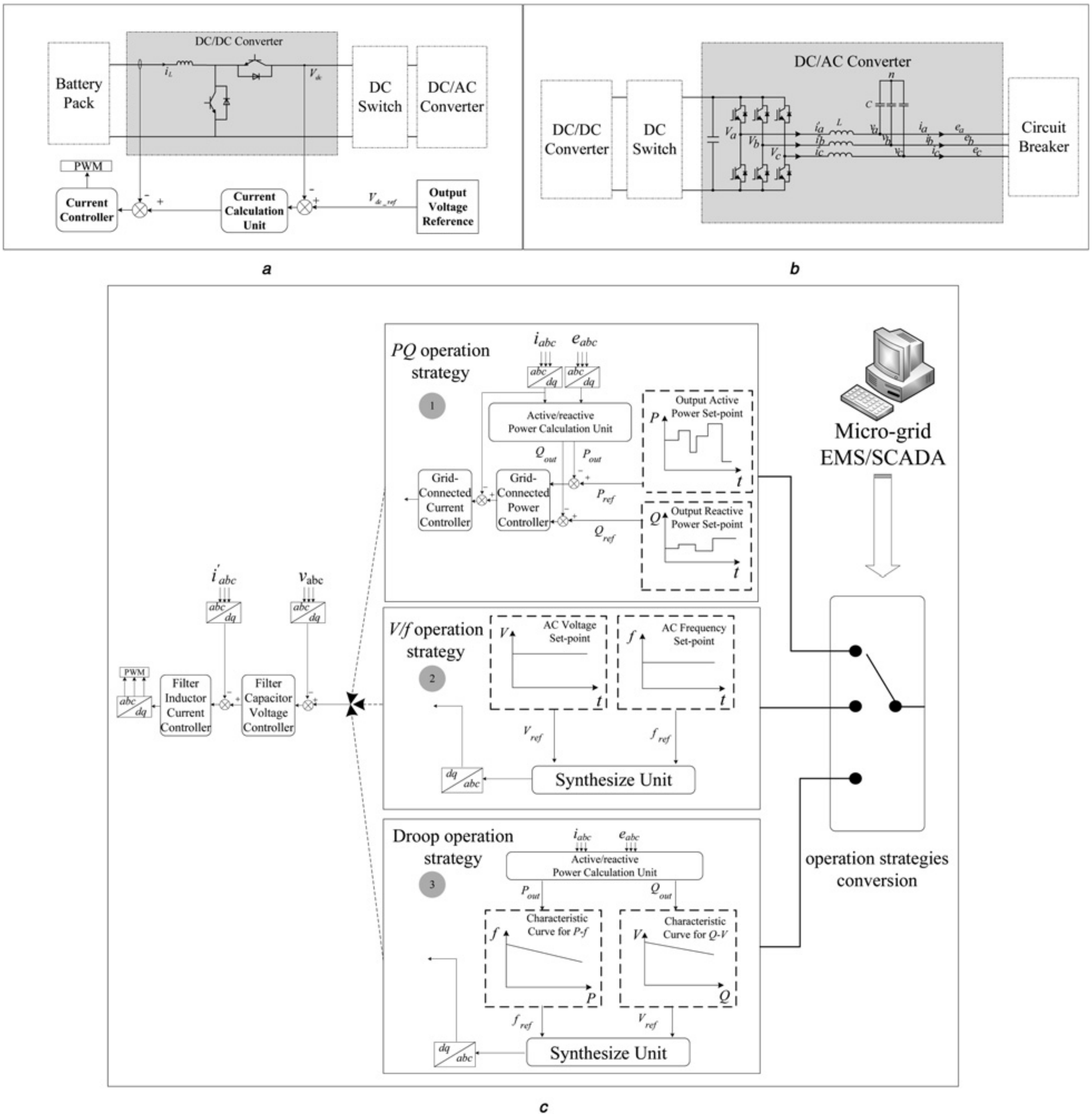


Fig. 3 *BESS application for micro-grid*

a Schematic diagram of BESS DC/DC converter
b Power circuit of BESS DC/AC converter for micro-grid
c Operation strategies of BESS DC/AC converter for micro-grid

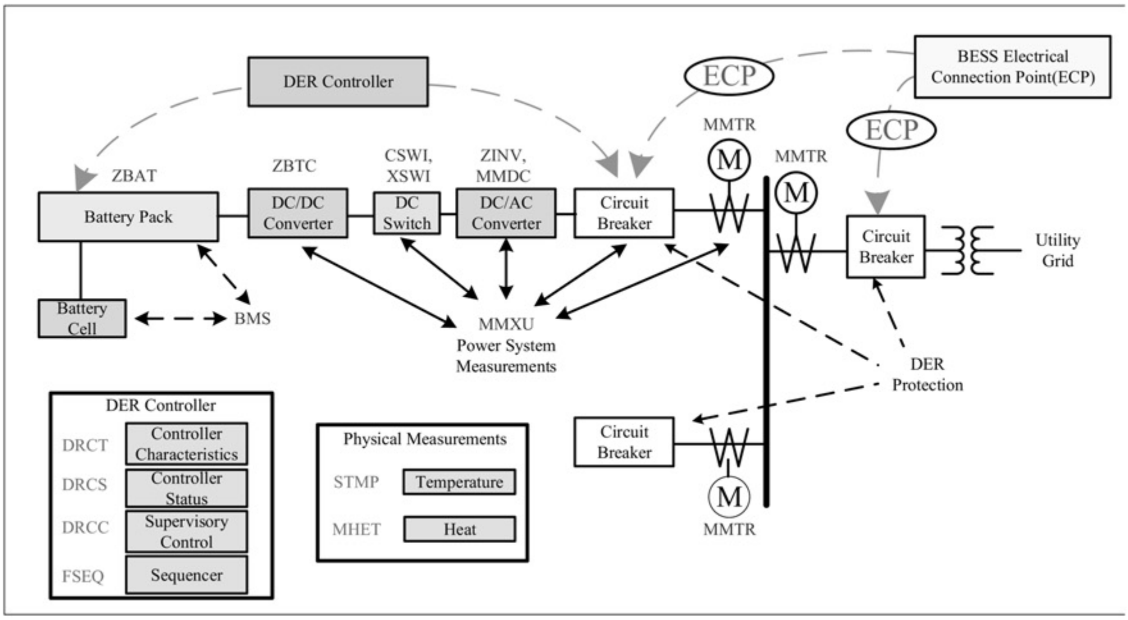
3.2.2 Constant voltage and frequency (V/f) operation strategy: When the utility grid has faults, micro-grid will transfer its grid-connected mode to the autonomous mode, and BESS could participate in voltage and frequency support to stably establish the system voltage. This requirement can be satisfied based on the constant voltage and frequency (V/f) operation strategy as shown in Fig. 3*c*.

For the V/f operation strategy, i'_{abc}, v_{abc}, $V_{\rm ref}$, and $f_{\rm ref}$ are required. The existing settings DO – *ZINV.OutHzSet* can be used to set $f_{\rm ref}$ determined by micro-grid EMS or local control instructions [14]. However, the existing measured values DOs for *ZINV* class mainly represent temperatures and fan speed, lacking of measured values DOs for representing i'_{abc} and v_{abc}, and settings DO to set $V_{\rm ref}$.

3.2.3 Droop operation strategy: BESS should participate in adaptive adjustment under the multiple BESS operation or BESS operation combining with other DER. This requirement can be satisfied based on the Droop operation strategy as shown in Fig. 3*c*.

The Droop controller is based on the active power–frequency (P–f) characteristic curve and the reactive power–voltage (Q–V) characteristic curve. For the Droop operation strategy, i'_{abc}, v_{abc}, i_{abc}, and e_{abc} are needful, and the P–f characteristic curve, the Q–V characteristic curve, $V_{\rm ref}$ and $f_{\rm ref}$ are also required. Then $V_{\rm ref}$ and $f_{\rm ref}$ can be obtained respectively through the P–f characteristic curve with $P_{\rm out}$ and the Q–V characteristic curve with $Q_{\rm out}$. $P_{\rm out}$ and $Q_{\rm out}$ can be obtained through the active/reactive power calculation unit based on i_{abc} and e_{abc}, respectively. Considering the existing measured values DOs for ZINV class [18], i'_{abc}, v_{abc}, i_{abc}, and e_{abc} should be represented by other extended DOs.

3.2.4 Auxiliary requirements: ZINV class should be extended for realising the special applications of BESS DC/AC converter for micro-grid through the PQ operation strategy, the V/f operation



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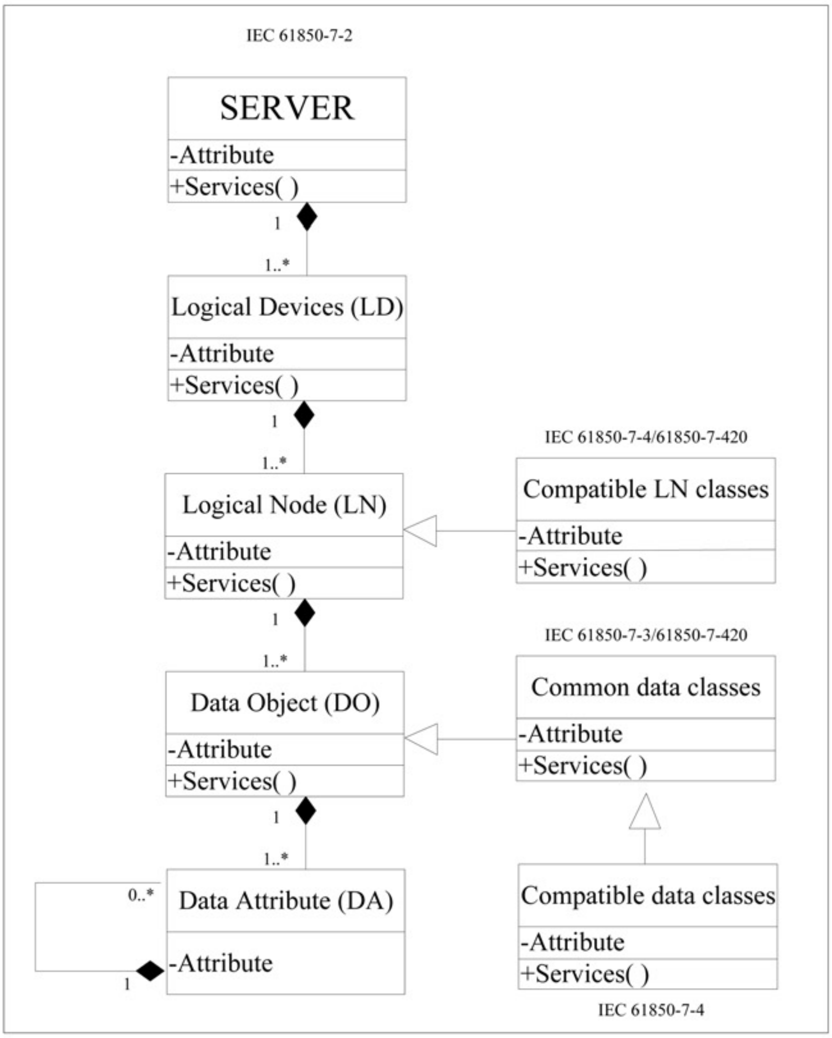

b

Fig. 4 *BESS data modelling*

a Conceptual organisation of BESS LNs
b IEC 61850 data model

Table 1 Extended DOs for ZBTC class

Data object name	CDC	Explanation	T	M/O/C
Settings				
RefDCV	ASG	output voltage reference value		O
HiBatsVAlm	ASG	high-voltage alarm level		O
LoBatsVAlm	ASG	low-voltage alarm level		O
BatsAProt	ASG	over current limit		O
Status information				
Loc	SPS	remote or local mode		O
OprAlam	ENS	alarm type		O
Measured values				
DCBusV	MV	output voltage		O
BatsA	MV	inductor current		O

strategy, and the Droop operation strategy mentioned previously. It also needs the controls DO to achieve the operation strategies conversion as shown in Fig. 3*c*.

Some status information about the local/remote mode, operation status, and alarm/fault of BESS DC/AC converter is also required by BESS IED or micro-grid EMS/SCADA for operation monitoring and advanced Management. In addition, the following functions could be required:

State of charge (SOC): Reflecting the battery pack available capacity. The maximum and minimum SOC should be confirmed.
Operation setting: When BESS adpots the *PQ* operation strategy, it can achieve the load shifting with discharging under peak loads and charging under low loads, thus the discharge/charge trigger thresholds should be confirmed, and it also can achieve the power dispatching for the point of common connection (PCC), then the power exchange value should be confirmed. In addition, it can be used to mitigate micro-grid power fluctuations especially caused by renewable energy output, so the power fluctuating trigger thresholds should also be confirmed.

However, the existing DOs in ZINV class cannot satisfy these requirements mentioned previous, thus some DOs needs to be extended for ZINV class.

Table 2 Extended DOs for *PQ* operation strategy

Data object name	CDC	Explanation	T	M/O/C
Measured values				
ACV	WYE	three-phase ECP voltages		O
ACA	WYE	three-phase grid-connected currents		O
CapV	WYE	three-phase filter capacitor voltages		O
InductA	WYE	three-phase filter inductor currents		O

Table 3 Extended DOs for *V*/*f* operation strategy

Data object name	CDC	Explanation	T	M/O/C
Settings				
OutVSet	ASG	AC voltage set-point		O
Measured values				
CapV	WYE	three-phase filter capacitor voltages		O
InductA	WYE	three-phase filter inductor currents		O

Table 4 Extended DOs for Droop operation strategy

Data object name	CDC	Explanation	T	M/O/C
Settings				
PfDroopSet	CSG	*P*–*f* characteristic curve		O
QVDroopSet	CSG	*Q*–*V* characteristic curve		O
Measured values				
ACV	WYE	three-phase ECP voltages		O
ACA	WYE	three-phase grid-connected currents		O
CapV	WYE	three-phase filter capacitor voltages		O
InductA	WYE	three-phase filter inductor currents		O

4 Extensional information model of BESS based on IEC 61850 for micro-grids

4.1 IEC 61850 data model

According to the applications and functions for micro-grid, the BESS devices can be divided into different logical device (LD) and LNs. Fig. 4*a* shows a conceptual view of different parts of BESS and their LNs for micro-grid according to IEC 61850 specification [14, 16]. The OO data modelling methodology is widely used for the implementation of the LNs application-view data model of the standard-IEC 61850 [7, 8]. Fig. 4*b* shows the relationships between IEC 61850 data model classes using the OO methodology for model representation, which is simply a template for the creation of LN model.

- *LDs:* represent virtual representations of BESS devices that perform control, supervision, or protection functions, created by combining several LNs.
- *LNs:* represent the specific device functionalities.
- *DOs:* represent groups of data attribute (DA), and can be organised into DataSet.
- *DAs:* are the endpoints of the IEC 61850 LN model, designated by functional constraint based on the application-view perspective.

Table 5 Extended DOs for ZINV class

Data object name	CDC	Explanation	T	M/O/C
Settings				
PfDroopSet	CSG	*P*–*f* characteristic curve		O
QVDroopSet	CSG	*Q*–*V* characteristic curve		O
OutVSet	ASG	AC voltage set-point		O
HiBatsSOC	ASG	high SOC alarm level		O
LoBatsSOC	ASG	low SOC alarm level		O
PeakLoadTr	ASG	peak loads trigger threshold		O
LowLoadTr	ASG	low loads trigger threshold		O
PeakLoadTar	ASG	peak loads shifting target		O
LowLoadTar	ASG	low loads shifting target		O
DispatWSet	ASG	PCC dispatching power set-point		O
FluWTr	ASG	power fluctuating trigger threshold		O
Status information				
Loc	SPS	remote or local mode		O
OprStat	ENS	operation status		O
OprAlam	ENS	type of alarm		O
Controls				
OprModChg	ENC	Operation strategies change Value — Explanation 0 — standby operation 1 — *PQ* operation 2 — *V*/*f* operation 3 — Droop operation 99 — other		O
Measured values				
ACV	WYE	three-phase ECP voltages		O
ACA	WYE	three-phase grid-connected currents		O
CapV	WYE	three-phase filter capacitor voltages		O
InductA	WYE	three-phase filter inductor currents		O
ACTotalP	MV	total active power		O
ACTotalQ	MV	total reactive power		O
SOC	MV	state of charge		O

IET Gener. Transm. Distrib., 2016, Vol. 10, Iss. 4, pp. 849–861

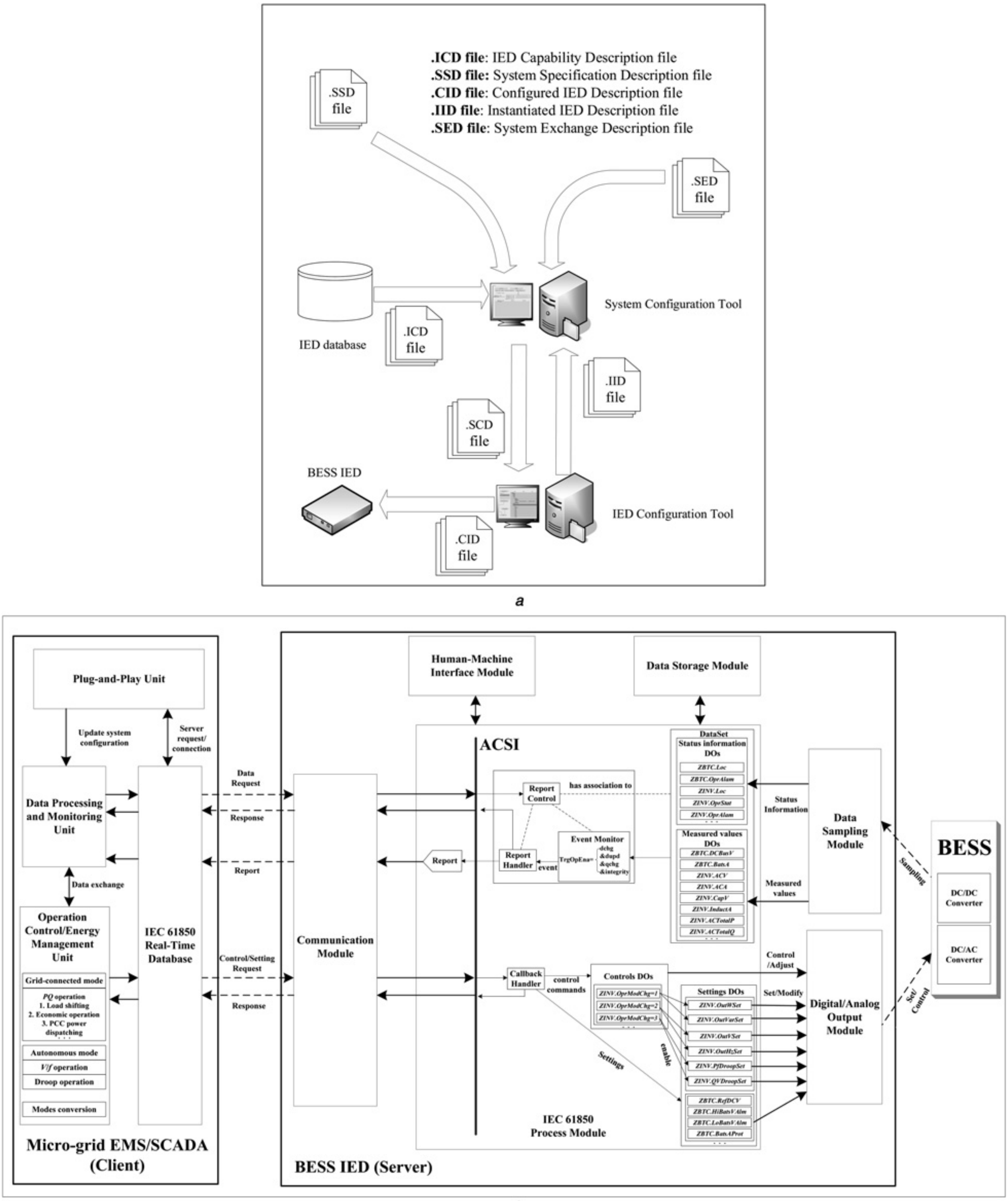

Fig. 5 *BESS operation based on IEC 61850 extensional information model for micro-grids*

a BESS extensional information model configuration procedures
b Designed functional modules of BESS IED and micro-grid EMS/SCADA for BESS operation
c Implementation procedures for BESS operation

4.2 Extensional information model for DC/DC converter

According to the requirement analysis for information model of BESS DC/DC converter, some DOs for ZBTC class are extended as shown in Table 1. The extended measured values DOs – *ZBTC.DCBusV* and *ZBTC.BatsA* represent V_{dc} and i_L, respectively. The extended settings DO – *ZBTC.RefDCV* is used to set V_{dc_ref}. The difference between *ZBTC.DCBusV* and *ZBTC.RefDCV* is used to provide input for the current calculation unit. Then, the difference between *ZBTC.BatsA* and the output of the current calculation unit is used to provide input for the current controller, to generate the pulse width modulation (PWM) signals for BESS DC/DC converter. The extended settings DOs – *ZBTC.HiBatsVAlm*, *ZBTC.LoBatsVAlm*, and *ZBTC.BatsAProt* are used to set the high-voltage alarm level, low voltage alarm level, and current limit, respectively. The extended status information DOs – *ZBTC.Loc* and *ZBTC.OprAlam* reflect the remote/local mode and alarm type, respectively.

4.3 *Extensional information model for DC/AC converter*

4.3.1 Active/reactive power (PQ) operation strategy: The corresponding DOs for ZINV class are extended as shown in Table 2. The extended measured values DOs – *ZINV.ACV*, *ZINV.ACA*, *ZINV.CapV*, and *ZINV.InductA* represent e_{abc}, i_{abc}, v_{abc}, and i'_{abc}, respectively. *ZINV.ACV* and *ZINV.ACA* are converted by the *abc*/*dq*-axis transformation, and then P_{out} and Q_{out} are obtained through the active/reactive power calculation unit. The difference between *ZINV.OutWSet* and P_{out}, and the difference between *ZINV.OutVarSet* and Q_{out} are used to provide input for the grid-connected power controller, to output i_{abc} reference values in the *dq*-axis. Then, the differences between *ZINV.ACA* and i_{abc} reference values in the *dq*-axis are used to provide input for the grid-connected current controller, to output v_{abc} reference values in the *dq*-axis. The differences between *ZINV.CapV* and v_{abc} reference values in the *dq*-axis are used to provide input for the filter capacitor voltage controller, to output i'_{abc} reference values in the *dq*-axis. Finally, the differences between *ZINV.InductA* and i'_{abc} reference values in the *dq*-axis are used to provide input for the filter inductor current controller, to generate the PWM signals for BESS DC/AC converter.

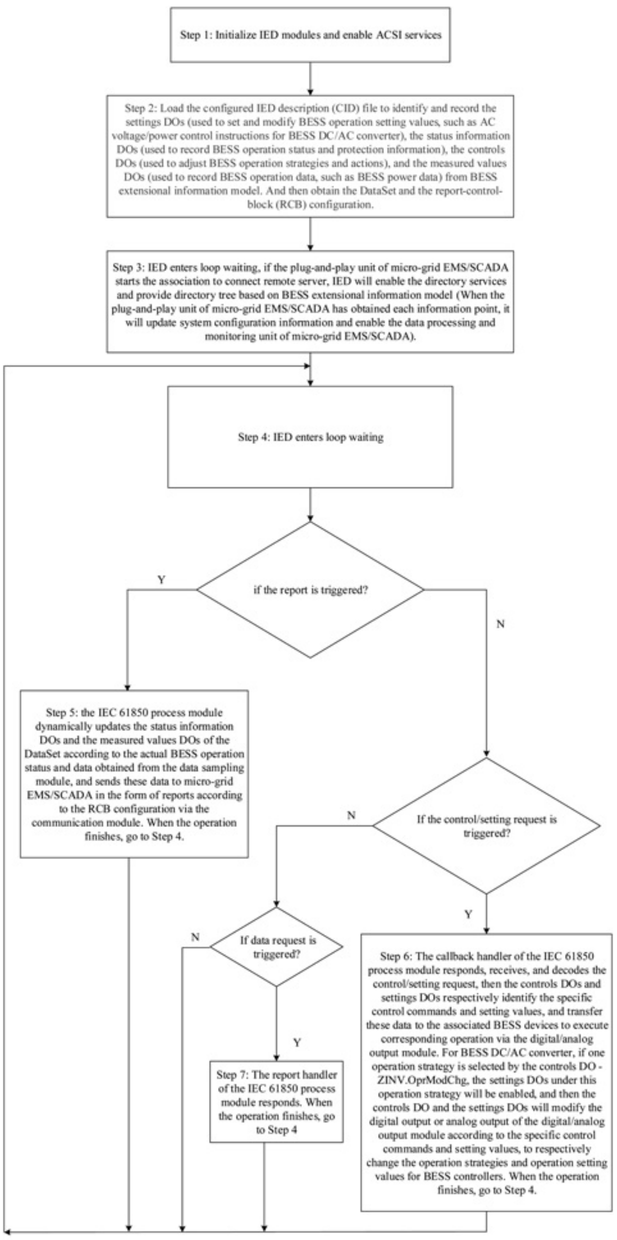

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Fig. 5 *Continued*

4.3.2 Constant voltage and frequency (V/f) operation strategy: The corresponding DOs for ZINV class are extended as shown in Table 3. The extended measured values DOs – *ZINV.CapV* and *ZINV.InductA* also respectively represent v_{abc} and i'_{abc}. The extended settings DO – *ZINV.OutVSet* is used to set V_{ref}. The v_{abc} reference values are synthesised through *ZINV.OutVSet* and *ZINV.OutHzSet*, and then converted by the *abc*/*dq*-axis transformation to generate v_{abc} reference values in the *dq*-axis. The differences between *ZINV.CapV* and v_{abc} reference values in the *dq*-axis are used to provide input for the filter capacitor voltage controller. The subsequent process of PWM generating is similar to that of the *PQ* operation strategy.

4.3.3 Droop operation strategy: The corresponding DOs for ZINV class are extended as shown in Table 4. The extended measured values DOs – *ZINV.ACV*, *ZINV.ACA*, *ZINV.CapV*, and *ZINV.InductA* respectively represent e_{abc}, i_{abc}, v_{abc}, and i'_{abc}. The extended settings DOs – *ZINV.PfDroopSet* and *ZINV.QVDroopSet* can be used to set the *P–f* characteristic curve and the *Q–V* characteristic curve, respectively. P_{out} and Q_{out} are obtained by *ZINV.ACV* and *ZINV.ACA* through the active/reactive power calculation unit. V_{ref} is generated according to Q_{out} and *ZINV.QVDroopSet*, and f_{ref} is generated according to P_{out} and *ZINV.PfDroopSet*. Then v_{abc} reference values are synthesised by V_{ref} and f_{ref} through the synthesise unit, and v_{abc} reference values in the *dq*-axis can be further obtained by the *abc*/*dq*-axis transformation. Then the subsequent process of PWM generating is similar to that of the *V*/*f* operation strategy.

4.3.4 DC/AC converter information model: The extended DOs established previously based on *PQ* operation strategy, *V*/*f* operation strategy, and Droop operation strategy for ZINV class are shown in Table 5. In addition, the extended status information DOs – *ZINV.Loc*, *ZINV.OprStat*, and *ZINV.OprAlam* respectively reflect the remote/local mode, operation status, and alarm type. The extended controls DO – *ZINV.OprModChg* can be used to change operation strategies. The extended measured values DOs – *ZINV.SOC*, *ZINV.ACTotalP*, and *ZINV.ACTotalQ* are responsible for representing BESS SOC, P_{out}, and Q_{out}, respectively. The extended settings DOs – *ZINV.HiBats*SOC and *ZINV.LoBats*SOC are used to set the high SOC alarm and low SOC alarm levels, respectively. The extended settings DOs – *ZINV.PeakLoadTr*, *ZINV.LowLoadTr*, *ZINV.PeakLoadTar*, and *ZINV.LowLoadTar* are used to set peak loads trigger threshold, low loads trigger threshold, peak loads shifting target, and low loads shifting target, respectively. In addition, the extended settings DOs – *ZINV.DispatWSet* and *ZINV.FluWTr* are used to set PCC dispatching power set-point and power fluctuating trigger threshold, respectively.

5 BESS operation based on IEC 61850 extensional information model for micro-grids

5.1 *Extensional information model integration configuration for micro-grids*

BESS LNs can be extended using the approach for the creation of LN model mentioned previously, and then will be implemented using the extensible mark-up language schemas released by IEC 61850 to instantiate the associated data information points [23, 24].

BESS IED is responsible for the automatic recognition of BESS extensional information model to realise its plug-and-play applications, and information exchange between BESS devices and micro-grid EMS/SCADA. IEC 61850-6 specifies the configuration description language for communication related to device IEDs and illustrates the system configuration description file, work procedures for IED, and the system configuration tools [25]. For BESS that is integrated into micro-grid, the specific configuration procedures according to IEC 61850-6 are shown in Fig. 5*a*.

IET Gener. Transm. Distrib., 2016, Vol. 10, Iss. 4, pp. 849–861

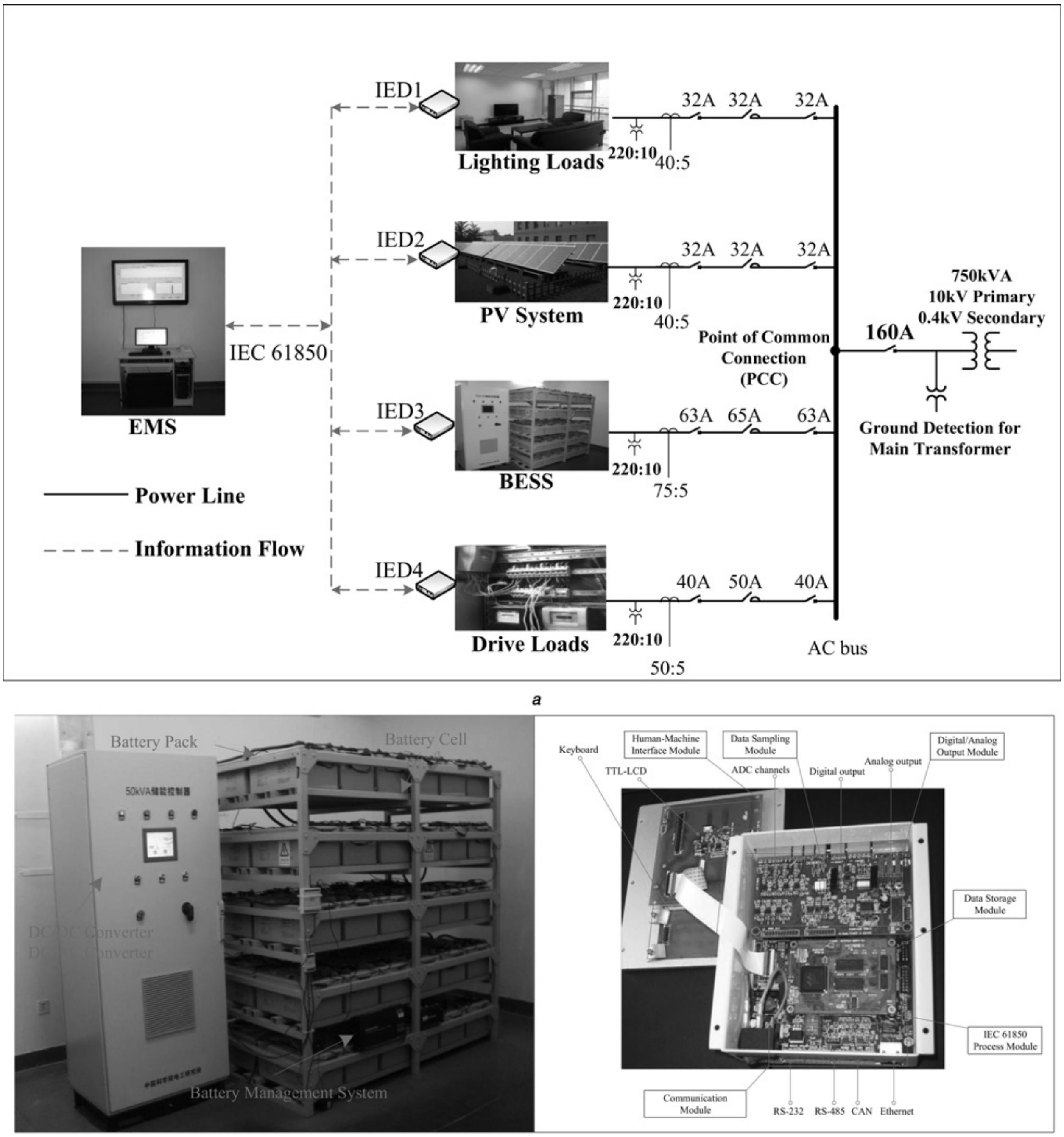


Fig. 6 *Micro-grid test system*

a Micro-grid test system structure
b Hardware of VRLA BESS
c Hardware of BESS IED

5.2 BESS information exchange based on IEC 61850 for micro-grids

BESS IED exchanges information particularly around the status information, measured values, control commands, and setting values between BESS devices and micro-grid EMS/SCADA based on the extensional information model. To realise BESS flexible operation for micro-grid, the cooperation of micro-grid EMS/SCADA and BESS IED is required. The designed functional modules of BESS IED and micro-grid EMS/SCADA are shown in Fig. 5*b*. As a manufacturing message specification (MMS) client, micro-grid EMS/SCADA includes:

IEC 61850 real-time database: It receives, stores, and sends the real-time IEC 61850 data.
Plug-and-play unit: If new BESS is integrated into micro-grid, then the unit will obtain its extensional information model and update system configuration information.
Data processing and monitoring unit: It is responsible for IEC 61850 data resolution based on the real-time data, historical data storing, and exchanging data with the operation control/energy management unit.
Operation control/energy management unit: It is responsible for analysing operation status of BESS and micro-grid, and generating control commands and management setting values for BESS under different operation strategies.

As a MMS server, BESS IED includes:

Communication module: It is integrated with communication ports, such as ethernet.
Human–machine interface module: keyboard and LCD are assembled for information display and configuration setting.
Data storage module: It reads, writes, and stores data for IED operation.
Data-sampling module: It is used to sample status information and measured values of BESS during its operation.
Digital/analogue output module: its digital/analogue output is used for BESS controllers input to regulate the operation setting values and operation strategies of BESS.
IEC 61850 process module: It is responsible for extensional information model identification and achieving the ACSI service request, service response, and service process.

Based on Fig. 5*b*, the specific implementation procedures for BESS operation are shown in Fig. 5*c*.

6 Operation tests of BESS based on IEC 61850 for micro-grids

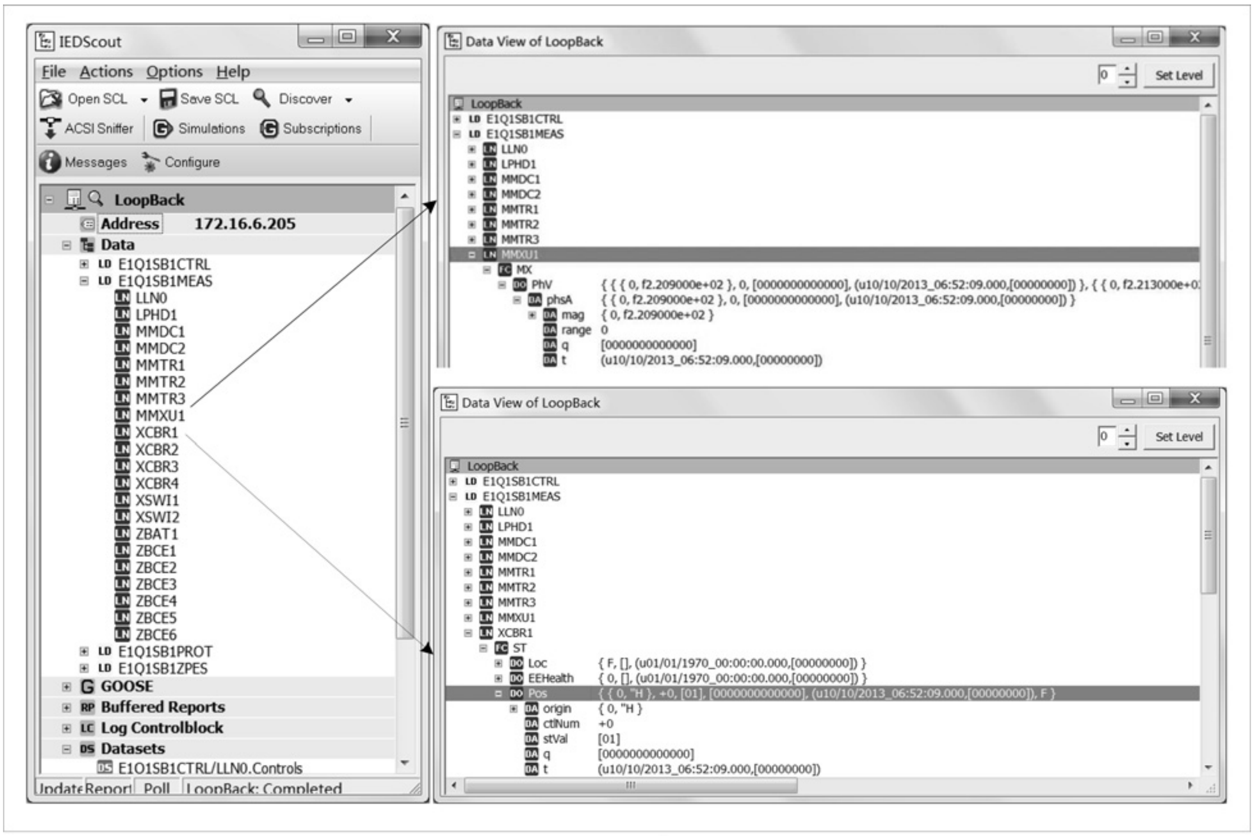
6.1 Micro-grid test system based on IEC 61850

The micro-grid test system, which is responsible for BESS information exchange and operation test, is established as shown in Fig. 6*a*. The DER comprises a PV system and a valve-regulated lead acid (VRLA) BESS shown in Fig. 6*b*. The power circuit of BESS is shown in Fig. 1*a*. The *PQ* operation strategy and the *V*/*f* operation strategy are selected for the micro-grid test system. The developed BESS IED is shown in Fig. 6*c*. BESS is equipped with the IED, and its extensional information model is downloaded to BESS IED though the IED configuration tools.

6.2 BESS information exchange test based on IEC 61850

Fig. 7*a* depicts the information exchange results between BESS and micro-grid EMS using the IEC 61850 test software-OMICRON IEDScout. As shown in Fig. 7*a*, micro-grid EMS obtains all LNs of BESS extensional information model and the corresponding DOs from BESS IED using the IEC 61850 communication services. The measured values DOs record the BESS operation data, e.g. *E1Q1SB1MEAS/MMXU1.PhV* is used to identify three-phase ECP voltages of BESS. The status information DOs record the BESS operation status, e.g. *E1Q1SB1MEAS/XCBR1.Pos* is used to identify the auxiliary contact position of the circuit breaks. The IED dynamically updates the status information DOs and the measured values DOs according to the actual operation conditions of BESS, and then exchange these information with micro-grid EMS according to the RCB configuration.

Communication network of the micro-grid test system based on IEC 61850 has a high transmission rate. The information transmission delay from micro-grid EMS to BESS controllers mainly depends on the performance of BESS IED. As shown in Fig. 7*b*, BESS IED takes less than 5 ms to identify the control commands received from micro-grid EMS and achieve the control reaction through outputting corresponding analogue signal via its digital/analogue output module. The test results show that BESS IED can meet the requirements of transmission time for control data exchange between the process level and the bay level specified in IEC 61850-5, and provide effective technologies for fast information exchange.

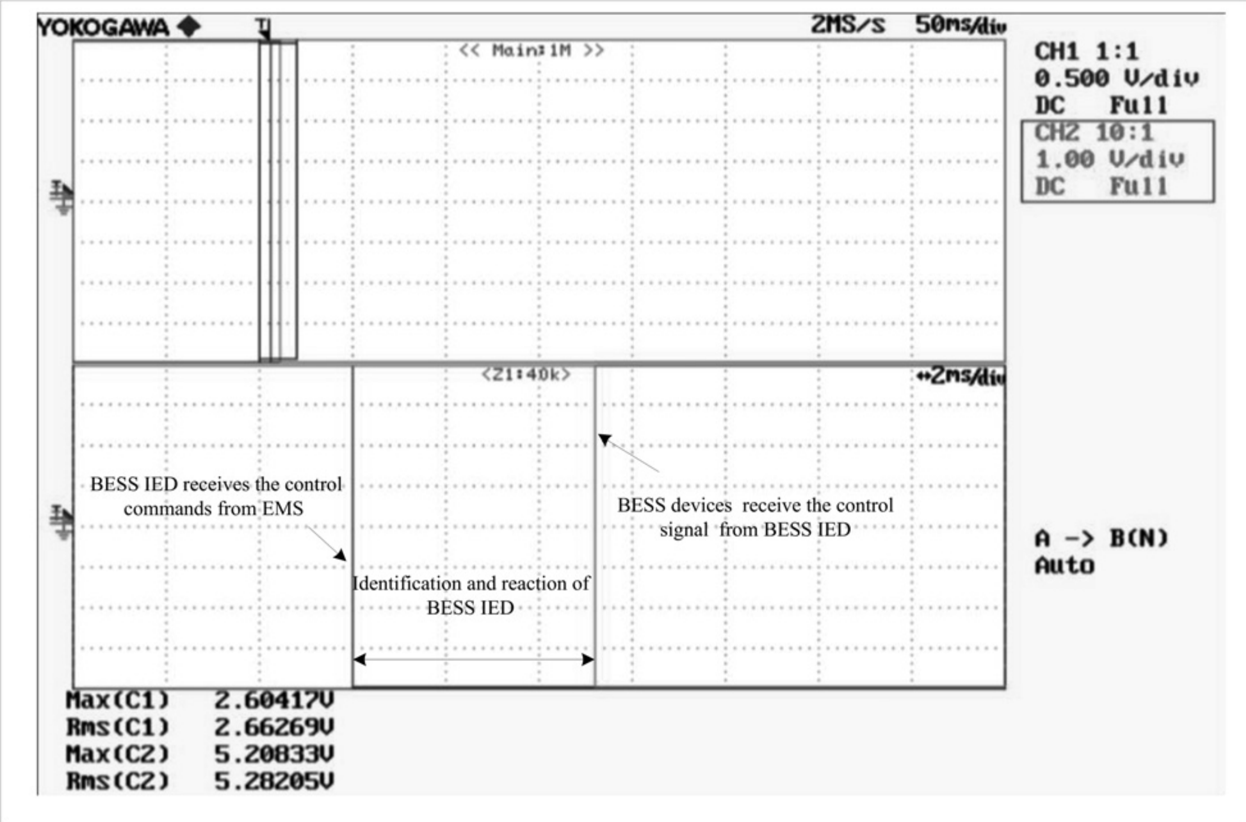


a

Fig. 7 *BESS operation test*

a BESS information exchange test
b Information exchange delay test
c Power curves based on the constant PCC power dispatching strategy of micro-grid
d Test results of operation strategies conversion

IET Gener. Transm. Distrib., 2016, Vol. 10, Iss. 4, pp. 849–861



b

Fig. 7 *Continued*

6.3 BESS operation test cases

6.3.1 Participate in optimal dispatching: BESS needs to rapidly respond the power setting values received from micro-grid EMS and correspondingly to regulate the active/reactive power output. Fig. 7*c* shows the power monitoring curves based on the constant PCC power dispatching strategy, which aims at achieving a constant power exchange between the micro-grid and the utility grid. As shown in Fig. 7*c*, BESS IED realises the complete communication with micro-grid EMS using the IEC 61850 communication services. The BESS active power setting values received from micro-grid EMS are accurately identified by the settings DO – *ZINV.OutWSet*. Then, *ZINV.OutWSet* directly adjusts the analogue signal output of IED digital/analogue output module for modifying BESS controllers input, to regulate P_{ref} for BESS DC/AC converter. Micro-grid can realise a stable PCC power exchange during the whole test process through the effective identification of BESS power setting values received from micro-grid EMS.

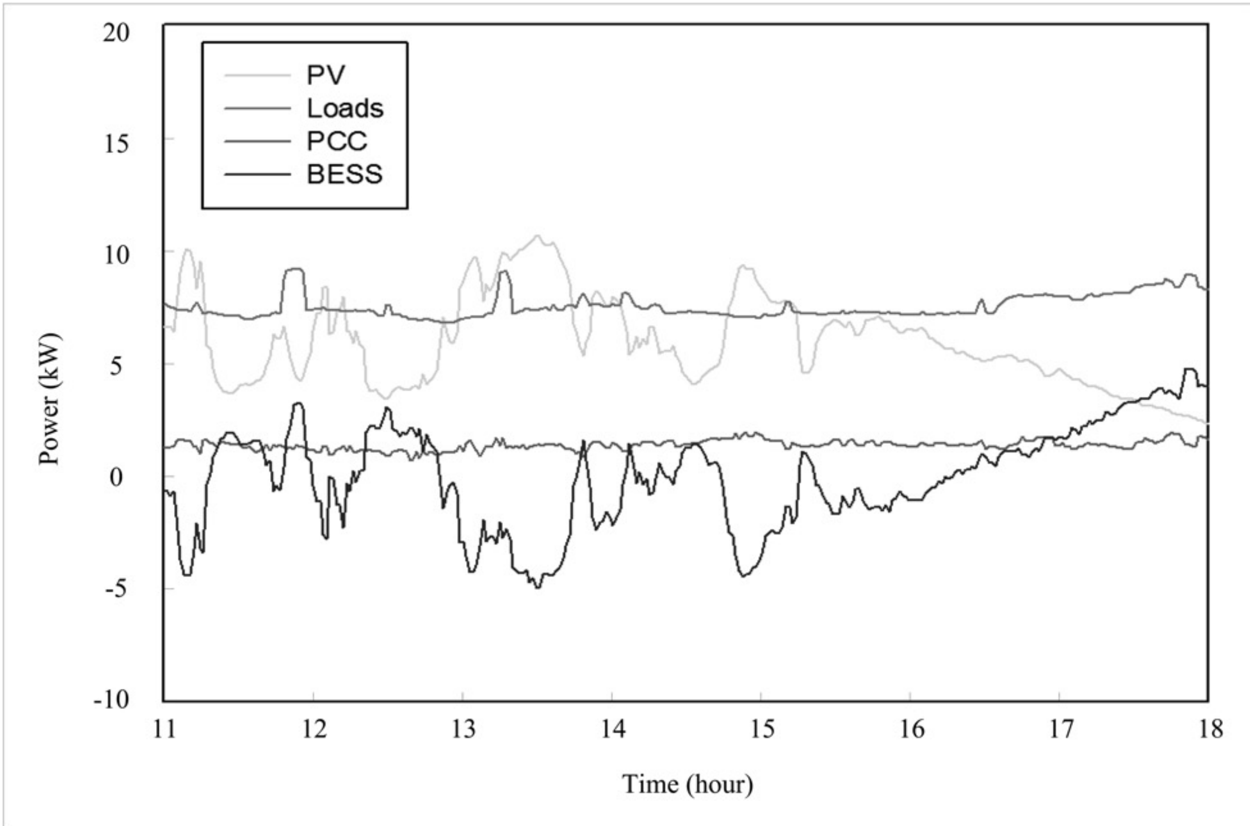
Meanwhile, the measured values DO – *ZINV.ACTotalP* reliably records the BESS power data for micro-grid EMS. The power monitoring data can accurately reflect the actual operation conditions of BESS, and thus provide the reliable information source for BESS advanced analysis and complex decision-making.

6.3.2 Operation strategies conversion: Though the BESS operation strategies conversion, micro-grid can seamlessly convert its operation modes, for example, conversion of the grid-connected mode to the autonomous mode and vice versa. Fig. 7*d* shows the test results when BESS IED receives the control commands from micro-grid EMS to convert the micro-grid operation modes, by converting the BESS *PQ* operation strategy to the *V*/*f* operation strategy. When BESS IED receives the control request, the controls DO – *ZINV.OprModChg* will extract the operation strategy control commands and output corresponding signal via IED digital/analogue output module for modifying BESS controllers input, to adjust BESS DC/AC converter from the *PQ* operation strategy to the *V*/*f* operation strategy. Meanwhile, the AC voltage and frequency set-points for BESS operation received from micro-grid EMS will be respectively identified by the settings DOs – *ZINV.OutVSet* (the default value is 220 V) and *ZINV.OutHzSet* (the default value is 50 Hz). Then, *ZINV.OutVSet* and *ZINV.OutHzSet* will directly regulate the analogue signal output of IED digital/analogue output module for modifying BESS controllers input, to adjust V_{ref} and f_{ref} for BESS DC/AC converter. As shown in Fig. 7*d*, the micro-grid AC bus voltage is well maintained at the sinusoidal characteristic during the operation strategies conversion, thereby ensuring an uninterrupted power supply. The experimental results show that BESS IED can accomplish the operation strategies conversion through rapid and accurate identification of BESS control commands and setting values received from micro-grid EMS, based on BESS extensional information model.

7 Conclusion

For many energy storage devices, their various types of communication ports and protocols make the flexible extension of devices capability and the plug-and-play applications in micro-grid large-scale system integration difficult. IEC 61850 provides standardised system language, communication services, and communication architecture to realise the rapid information modelling and the standardised information exchange for energy storage system. However, the existing object models for energy storage system do not fully meet its requirements of actual applications for micro-grid. In order to realise energy storage system flexible operation for micro-grid, its object models need to be developed in a further step.

According to the detailed requirements analysis for BESS operation under the typical BESS applications, including requirement analysis for information model of DC/DC converter and DC/AC converter under *PQ* operation strategy, *V*/*f* operation



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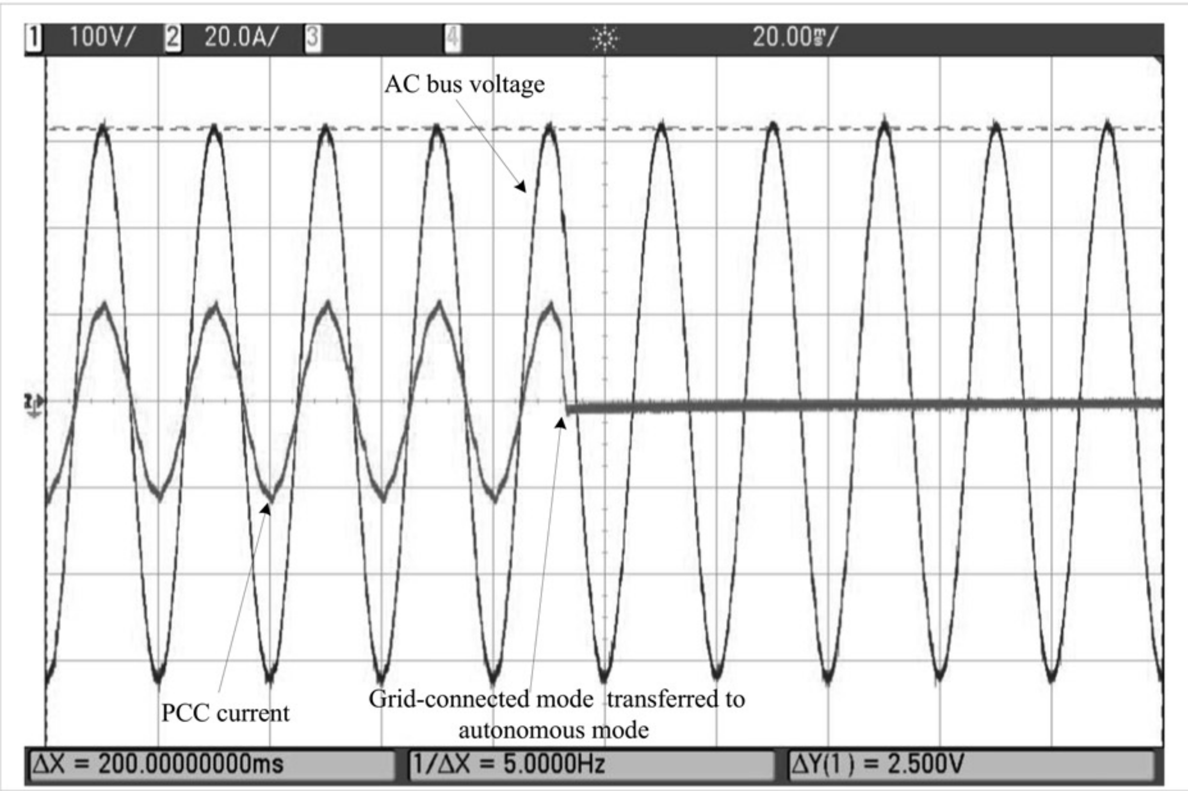

d

Fig. 7 *Continued*

strategy, and Droop operation strategy, the requirements of BESS information model for micro-grid was proposed. Then the OO data modelling methodology was used to build IEC 61850 data model of BESS controllable power converter and its extensional information model. Further, the integration configuration of BESS extensional information model for micro-grids was achieved based on the specific configuration procedures according to IEC 61850-6, and the output CID file was downloaded into BESS IED.

Based on this, the functional modules of BESS IED used as a MMS server and micro-grid EMS/SCADA used as a MMS client for BESS operation were designed, and their specific work procedures for BESS operation was further presented in detail.

Further, the micro-grid test system based on IEC 61850 and BESS IED were developed. Through the test system and proposed information exchange implementation procedures, information exchange test was performed, and BESS operation tests including optimal dispatching and operation strategies conversion based on IEC 61850 were verified. The BESS power setting values received from micro-grid EMS ware accurately identified by the settings DO of BESS extensional information model to dynamically adjust the power output of BESS DC/AC converter, meanwhile, its controls DO accurately identified the operation strategy control commands received from micro-grid EMS to adjust BESS DC/AC converter from the *PQ* operation strategy to the *V*/*f* operation strategy, and its measured values DO reliably recorded the power data during BESS operation for micro-grid EMS.

The results demonstrated that proposed BESS extensional information model and the implementation framework for BESS operation including information modelling, integration configuration and information exchange between BESS IED and micro-grid EMS/SCADA in this paper can provide effective techniques for realising flexible operation of energy storage system for micro-grid, and solving the specific problems in actual applications of BESS. The research hopes to contribute to the rolling revision and actual applications of IEC 61850 standards and technical reports.

This paper mainly focuses on the extensional information model of BESS using IEC 61850 MMS, including BESS IED as a MMS server in the bay level of micro-grid, and EMS/SCADA as a MMS client in the station level of micro-grid. The information model and data exchange for BESS in the process level have not yet been involved, such as publish/subscribe of the sampled values messages, and the generic object oriented substation event messages. The research in this area will be further performed in the future.

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