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Design, Control and Monitoring of an Offline Mobile Battery Energy Storage System for a Typical Malaysian Household Load Using PLC

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ABSTRACT

Battery energy storage system (BESS) is used in many practical applications including unin-terruptible power supplies (UPS), portable devices, electrical vehicles and renewable energy systems. To utilize BESS effectively, an efficient control operation is required. Various con- trollers have been introduced in the open literature. However, they are not considered the best fit due to their limitations. This includes their incapability of handling high-power rating BESS, low noise immunity, short life cycle and limited number of input and output interfaces. In this paper, the programmable logic controller (PLC) is used to control and monitor a 158.8 kWh offline BESS for a typical Malaysian household. TIA portal V13 soft- ware by Siemens is used to program the proposed PLC control. Human machine interface (HMI) system is used to monitor and simulate the control performance. The results show that the PLC approach provides an efficient and reliable control of the BESS in which a compact protection against the battery overcharging, under-discharging and overheating is achieved.

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1. INTRODUCTION

Electrical energy storage is the process through which the electrical energy can be converted into any other form of energy for storing purposes, then converted back to electrical form when needed [1]. Several technologies for energy storage have been developed across the disciplines; such as electrical, electrochemical, thermal and mechanical technologies. Capacitors, rechargeable batteries and flywheels are the most famous devices for storing energy in electrical energy, electrochemical and mechanical forms respectively [2]-[4]. Stored electrical energy can be used in several applications such as uninterruptible power supply (UPS), portable devices, transport vehicles, and alternative energy systems, and improving the stability and reliability of network grid [5].

Battery energy storage system (BESS) is the technology of storing the electrical energy into rechargeable batteries. Based on the operating principles and configuration of BESSs, they can be categorized into different types such as online BESS and offline BESS [6]. The main advantages of online BESS are: ensuring the quality of the power supply to the load, supplying the critical loads during the main failure of the main power supply [7]. It is important to note that the offline BESS works alone to provide the required energy to the loads. Furthermore, offline BESS is crucial for a number of applications, such as supplying the isolated areas (e.g. islands and villages); and autonomous systems, such as electric vehicles and robots [8],[9].

Among all rechargeable batteries such as nickel cadmium and lead acid, lithium-ion batteries have become an excellent alternative energy storage technology because of several reasons, namely: their higher energy density, volumetric power, reliability, precise operation conditions and direct energy storage. Therefore, they can be utilized either for a large energy storage system such as BESS and electric vehicles or other various applications. This includes mobiles, laptops, backup energy devices, and hybrid electric and electric vehicles [10]. However, according to [11], lithium-ion batteries are complex electrochemical devices. This complexity stems from the nonlinear relations be- tween various battery parameters, the significant change of battery characteristics over its time cycle due to aging and degradation, and the dependence of the battery behavior on various external and internal conditions, like current, volt- age, temperature and battery impedance. Therefore, every BESS requires an effective control and careful monitoring to guarantee efficient and safe operating conditions [12].

Many researches with different control approaches have been carried out regarding control and monitoring of battery storage system in different applications, especially in renewable energy systems, smart grid, and electric vehicles. A management system was designed for monitoring and balancing a multicell battery based on the micro controller AVR [13]. However, an additional cost added for using a multiplexer to handle the lack of inputs peripherals of the AVR. Furthermore, in [14], ATmega16 was used for controlling the charging process of lithium-ion batteries. PLC is used effectively in BESS. PLC for management and control of distributed energy production consisted of three units, namely photovoltaics unit, wind unit and biomass unit, and battery [15]. Also, PLC was used for control hybrid energy storage system, which was a power system consists of a stand-alone photovoltaic, pumped water energy storage and battery pack has been developed for a village [16]. PLC was utilized for control battery energy storage system integrated with solar system [17], PLC for control battery discharge current [18], and, finally, an online high-power rating has been controlled and monitored by exploiting the advantages of the PLC S7 1200 [19].

This work introduces the use of PLC for controlling and monitoring an offline BESS for supplying a typical Malaysian load for a week time. The PLC controller operates based on a centralized control architecture which allows for the system complexity and cost to be reduced. First, a comprehensive design of the BESS is discussed to determine the optimal sizing of BESS. For controlling and monitoring the BESS, a PLC S7-1200 and supervisory control and data acquisition (SCADA)/ HMI are used respectively. The paper starts by giving a general design of the BESS, followed by a design of an offline mobile 158.8 kWh BESS based on standard Malaysian load. After that, the operation and simulation of the proposed control are discussed. Finally, a conclusion is drawn.

2. RESEARCH METHOD

The methodology of the paper starts by giving general design steps of the BESS. Then, an offline mobile BESS with a total capacity of 158.8 kWh is designed based on a standard Malaysian household load.

2.1. Battery Energy storage design

During last decade, the need for battery energy storage systems has increased rapidly due to the decrease in the price of the batteries and the recent improvement in their performance. Therefore, a comprehensive description of the main steps to design a BESS is needed to ensure the correctness of the design. However, the design can be divided into four steps as follows:

2.1.1. Determining the maximum power, current, and the daily energy demand of the load

2.1.1.1. The maximum load power ($P_{max-load}$)

The $P_{max-load}$ is the sum of the rated power of each electrical device (P_{rated}). If n is the total number of the electrical appliances, then:

$$P_{max-load} = \sum_{i=1}^{n} P_{rated} i \quad (kW) \tag{1}$$

Moreover, the maximum load current ($I_{max-load}$) is calculated based on the power factor of the load ($cos\varphi$), load voltage (V_{load}) and type of the system whether it is a single-phase or a three-phase system. The ($I_{max-load}$for single-phase system is obtained using the following equation:

$$I_{max-load} = \frac{P_{max-load}}{V_{load} * cos\varphi} \ (A) \tag{2}$$

However, when the system is a 3-phase system, the V_{load} is the line-to-line voltage. Therefore, the equation to obtain the $I_{max-load}$ will be:

$$I_{max-load} = \frac{P_{max-load}}{\sqrt{3} * V_{load} * cos\varphi} \ (A) \tag{3}$$

2.2.2.2. The daily energy demand(E_{load})

based on the $P_{rated}i$ and daily average usage hours ($h_{usage}\, i$), the E_{load} of the load can be calculated as follows:

$$E_{load} = \sum_{i=1}^{n} P_{rated}i \ * \ h_{usage}\, i \ (kWh) \tag{4}$$

2.1.2. Inverter Selection

The $P_{max-load}$, $I_{max-load}$, and desired DC bus voltage (V_{DC-bus}) are mainly three considered criteria for inverters selection as follow:

$$\begin{aligned} &P_{rated.inv} > P_{max-load} \\ &I_{rated.inv} > I_{max-load} \\ &V_{input-inv} = V_{DC-bus} \end{aligned} \tag{5}$$

Therefore, the inverter input power P_{DC} can be calculated based on the inverter efficiency (η_{inv}):

$$P_{input-inv} = P_{DC} = \frac{P_{load}}{\eta_{inv}} \ (kW) \tag{6}$$

Similarly, the daily energy demands (E_{DC}) is calculated as follows:

$$E_{DC} = \frac{E_{load}}{\eta inv} \ (kWh) \tag{7}$$

In some cases, the above calculations are dispensable when costumers provide BESSs designers directly with E_{load} or even E_{DC} especially in the DC systems.

2.1.3. Designing the battery pack capacity (kWh)

This section helps the designer to optimize the size of the battery pack of the designed BESS based on the BESS specifications such as load and backup time [20].

1. Battery pack capacity ($C_{pack}\ (kWh)$)

The C_{pack} can be calculated by considering the E_{DC} and days of autonomy (N_d). The days of autonomy is the period required for the BESS to continuously supply electricity to the load before being recharged. The equation used to determine the capacity of the battery pack is:

$$Cpack \ = \ E_{DC} * \ Nd \ \ (kWh/days) \tag{8}$$

2. Battery pack capacity ($C_{pack}\ (kAh)$)

$$C_{pack} = \frac{C_{pack}(kWh/days)}{V_{DC-bus}} \ (kAh/days) \tag{9}$$

3. Minimum battery capacity in each series $\left(C_{battery}\ (kAh)\right)$

by considering the maximum desired number of parallel strings (N_p), temperature factor (T_m), and depth of discharge (DOD) factor of the batteries. T_m and DOD can be set at the value of 1 to find the initial minimum battery capacity as follow [21]:

$$C_{battery}= \frac{C_{pack}(kWh/days) * \mathrm{T_m}}{Np * DOD} \ (kAh) \tag{10}$$

Then, using the information of $C_{battery}$ and $V_{DC\ -bus}$, a real battery is chosen by rounding up this value to near standard capacity (C_{rated}) with a battery rated voltage (V_{rated}).

4. Maximum number of batteries in each series string ($\mathrm{N_s}$)

$$N_S= \frac{V_{DC-bus}}{V_{rated}} \ batteries \tag{11}$$

5. Total number of batteries in the BESS (N_{total})

$$N_{total}= N_p * N_s \ batteries \tag{12}$$

2.1.4. Rectifier Selection

Specifications of the selected rectifier (battery charger), such as output voltage (V_{rect}) and charging current (I_{rect}), totally depend on the battery specifications such as C_{rated}, V_{rated} and battery maximum charging current (I_{c-max}). Then, a charger with proper specifications can be chosen.

2.2. An offline mobile bess for a typical malaysian household

In this section, BESS is designed for a specific load (Malaysian typical household). Then the PLC is harnessed for controlling and monitoring the BESS. While the last section presents the measurement acquisition system.

2.2.1. Rectifier selection

An offline mobile BESS, where the BESS is charged in one place and discharged in another once, is designed to supply a single phase typical Malaysian household load. Furthermore, this BESS is designed with a weekly energy capacity (Nd =7 days) based on the rated power of each electrical device and daily average usage during weekdays and weekends [22]. Table 1 shows, in detail, the process of determining the weekly energy demand.

Table 1. kWh residential consumption for a typical Malaysian household

Electrical Load	No. of Appliances	Power (W)	Daily Average Usage (h)		Total Hours per Week	Energy Demand (kWh)
			Weekdays	Weekends		
Air Conditioner	1	750	5.05	4.75	34.75	26.06
Tv	1	150	5.7	8.15	44.8	6.72
Iron	1	1000	0.53	0.46	3.57	3.57
Refrigerator	1	1200	8.11	8.11	56.77	68.12
Washing Machine	1	850	1.04	1.04	7.28	6.18
Lighting	5	180	5.67	5.45	39.25	7.06
Standing Fan	1	75	11.55	12.04	81.83	6.14
Rice Cooker	1	730	0.72	0.73	5.06	3.69
Kettle	1	850	0.48	0.44	3.28	2.79
Toaster	1	800	0.16	0.14	1.08	0.86
Blender	1	300	0.26	0.19	1.68	0.50
Hair Dryer	1	1125	0.09	0.05	0.55	0.62
Other Devices		300	3	5	25	7.5
Total Power Required		8310				
Total Weekly Energy Required						139.81
Average Daily Energy Required						19.973

The BESS is designed with a total capacity of C_{pack}=158.876 kWh based on the $P_{max-load}$ after considering a 20 % safety factor, and the daily energy demand, E_{load}= 19.973 kWh, N_d and η_{inv}. A summary of the design results, a suggested off-shelf inverter, rectifier and lithium-ion batteries are shown in Table 2 with respect to the V_{load}= 240 V (single phase of distribution network in Malaysia), $V_{DC\ -bus}$= 48 V and N_s =1.

Table 2. The designed offline mobile BESS specifications

Battery Pack Specifications						
Type	$E_{DC}(kW)$	C_{pack} $(kWh/days)$	C_{pack} $(kAh/days)$	V_{DC-Bus} (V)	N_p	N_{total}
Offline	22.269	158.876	3.3099	48	12	12
Lithium-ion Batteries Specifications						
Model	$Crated$ (Ah)	V_{rated} (V)	$V_{max}(V)$	V_{min} (V)	T_m	DOD
SB48300	300	48	64	40	1	1
Inverter and Rectifier Specifications						
Type	Model	P_n (kW)	η	V_{in} (V)	V_{out} (V)	
Inverter	PICOGLF10KW48V240VS	10	0.88	48	240	
Rectifier	SC-MAK Series Switch	14.4	0.92	400±15	48	

Figure 1 shows the block diagram of the BESS, including inverter, battery pack, rectifier and control and monitoring unit as an integrated mobile unit. Therefore, at any operation condition, the BESS can be connected either to the grid or to the load.

2.2.2. PLC Programming

The main advantages of PLC in addition to its low power consumption, are the high reliability and high interference immunity. A centralized architecture, using one PLC, have been used to control the system which results in a cheaper, more compact setup. Hence, it makes the system installation more convenient. Further, the integration of the PLC and HMI is accomplished for monitoring the parameters of BESS and facilitating the troubleshooting and diagnostic of the system. PLC S7-1200 CPU 1215 DC/DC/DC and KTP700 Basic HMI panel are programmed using Siemens software, totally integrated automation (TIA) portal V13. All functions have been controlled automatically such as start/stop operating sequences, energy flow control to and from the batteries and ensure the communication tasks between the BESS and HMI of the designed BESS.

The programming algorithm of the PLC is illustrated in Figure 2. First, the VDC −bus and battery pack temperature are monitored. The BESS will be shut down immediately if one of these parameters exceeds the allowable values to prevent the overcharging or under discharging and overheating cases. Then, either in charging or discharging mode, the lithium-ion battery parameters (SOC(i) and charging current Ic(i) or discharging current Id(i)) are monitored to protect each battery in the battery pack from the occurrence of a potentially damaging overcharging or under discharging events.

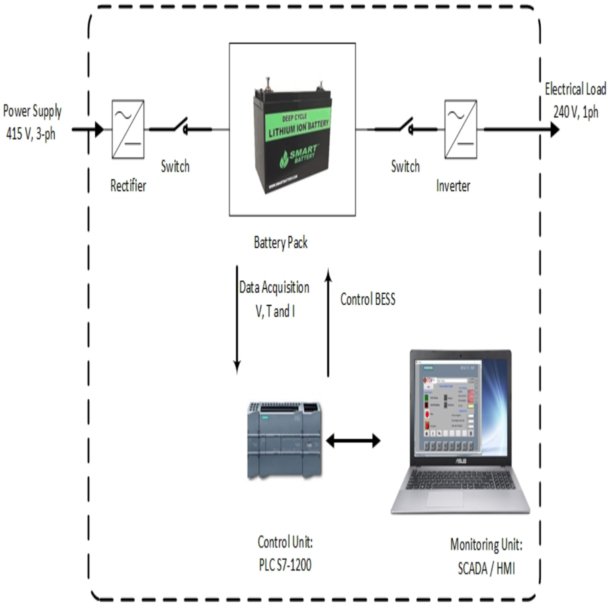


Figure 1. Block diagram of the designed offline mobile BESS

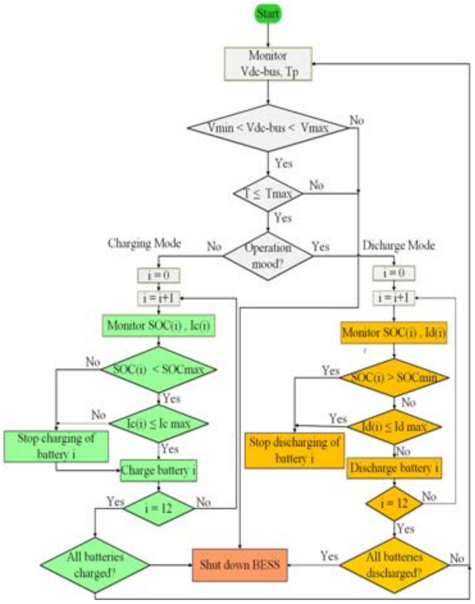


Figure 2. PLC flow chart

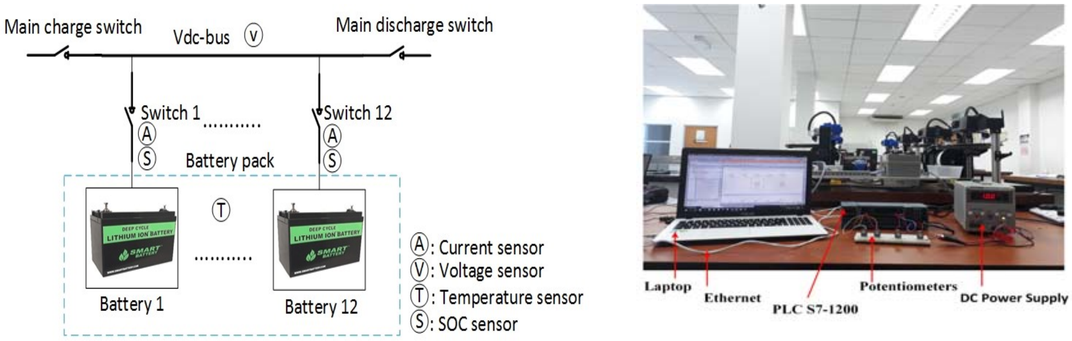
2.2.3. Measurement acquisition system

To achieve an accurate and precise control of the BESS, all system parameters are monitored using different types of sensors, in which the selected sensors are chosen with an output 0 to10 volts to establish the connection with analog input modules of the PLC. The data acquisition system for the designed BESS consists of 26 sensors which are $V_{DC\ -bus}$ sensor, temperature sensor, 12 DC current sensors and 12 SOC sensors are used to control and monitor the BESS, as shown in Figure 3a.

Due to the high cost of lithium-ion batteries for 158.8 kWh BESS, in which 12 batteries are needed with 300 Ah rating, the real implementation is difficult. Therefore, to test the operation of the system, alternatively, potentiometers with various output from 0 to 10 volts are fairly used to represent the real output of the BESS sensors. Figure 3b shows the data acquisition system during the case of using four potentiometers; they represent the voltage sensors, temperature and current sensor and SOC sensor of the first battery. In addition, PLC is connected to the laptop using Ethernet.
Inverter Selection

3. RESULTS AND DISCUSSION

In this work, besides programming the PLC, KTP700 Basic HMI panel touch screens have been built to achieve continuous monitoring of the designed offline BESS using TIA portal basic V13 SP1 WinCC. For safe operation of the BESS, three issues were considered (1) voltage protection, the battery voltage range is 40 to 64 V, which represents the minimum and maximum cut-off voltage, respectively. 2) overheating protection, the battery temperature should not exceed 70 C. 3) overcharging and under discharging protection, by disconnecting the batteries when they are either fully discharged (SOC= 0 %) or fully charged (=100 %)). The finding result can be divided into two main cases based on the operating conditions.



(a) (b)

Figure 3. a) The sensors of the designed BESS and b) Data acquisition system

3.1. BESS under safe operating conditions

In this case, the proposed control under safe operation mode of the BESS has been tested. The SCADA has been used to demonstrate the operation. The power control screen is used to control the power flow either during charging or discharging mode, Figure 4a shows the screen during charging mode. Several functions are controlled by screen namely: stop charging or discharging using stop button, shut down the whole system from the emergency button and, during initial stage, inserting specifications of the lithium-ion batteries (rated capacity, maximum cut-off voltage and minimum cut-off voltage).

Batteries interface gives information about the BESS status parameters, which are the total charging current, total load current, power delivery, $V_{DC\ -bus}$ and temperature. Figure 4b shows the batteries interface during charging mode. The total charging current is 3600 A, since the output values of the current sensors (potentiometers) of each battery are set at 10 V which is equivalent to 300 A. Similarly, the $V_{DC\ -bus}$ sensor and the temperature sensor of battery pack are set at 4.8 V and 5 V, these initializations are equivalent to 48V and 50 C respectively.

Moreover, batteries interface includes four sub-interface screens for monitoring the current and SOC of the 12 lithium-ion batteries. Each three batteries are grouped in one sub-screen (first group: Batteries 1, 2 and 3; group 2: Batteries 4, 5, and 6; group 3: Batteries 7, 8, and 9; and group 4: Batteries 10, 11, and 12).

Figure 4c shows Batteries 1, 2 and 3 interface during charging mode. This interface provides the HMI operator with the necessary information about the battery charging or discharging current and SOC.

Cn (Ah) 300.00
Max Vcut-off (v) 64.00
Min Vcut-off (v) 40.00

(a)

Total Charging Current (A) 3600.00
Total Load Current (A) 0.00
Power Delivery (kW) 0.000
DC Bus Voltage: Sensors (V) 4.80
DC Bus Voltage (V) 48.00
Temperature: Sensors (V) 5.00
Temperature (°C) 50.00

(b)

	Battery 1	Battery 2	Battery 3
Batt. Current: Sensors (V)	10.00	10.00	10.00
Batt. Current (A)	300.00	300.00	300.00
SOC: Sensors (V)	8.00	5.00	2.00

(c)

Figure 4. HMI interfaces of (a) Power control, (b) Batteries panel and (c) Batteries 1,2 and 3

3.2. BESS unsafe operating conditions

PLC offers at the same time a full and automatic protection to each battery as well as the whole the battery pack. Table 3 summarizes the main causes of the unsafe operating conditions of the BESS and the response of the PLC control approach to each case.

In brief, a reliable and efficient controlling was achieved using the proposed PLC control approach for BESS. Among the merits of this approach are compact protection against the battery overcharging, under-discharging and overheating. This is superior to the conventional control techniques (using microcontrollers [14], [15]) in which the limitations of restricted input and output ports, noise immunity and shortage lifespan are effectively overcome. There are some works on the PLC implementation and control for battery applications [16]-[19]. However, this work has distinctly considered the whole system design and presented the PLC control under several circumstances. Hence, it provides a detailed and thorough understanding of using PLC in BESS system. In addition, the full inclusion of SCADA for system monitoring in this work results in high controllability, observability and reliability of the BESS.

Table 3. Summary of the unsafe operation cases and the response of the PLC

Parameters	Charging Operation Case	Discharging Operation Case	Controller Action (PLC)
Temperature	T >70º overheating		shutdown BESS
DC-bus Voltage	V>64 V over charging voltage	V <40 V under discharging voltage	shutdown BESS
Battery Current	I >300 A overcharging current	I <300 A discharging current	disconnect this battery and shutdown BESS after disconnecting all batteries
Battery SOC	SOC = 100 %	SOC = 0 %	

4. CONCLUSION

In this work, a PLC control scheme is introduced for a high-power offline BESS. The proposed control has the advantages of handling high-power rating BESS and providing a fully automated protection from undesired voltage, current and temperature levels. The proposed control method is targeted for a typical Malaysian residential load with a capacity of 158.8 kWh. Based on the design, suitable off-the-shelf devices that include an inverter, rectifier, and 12 lithium-ion batteries (300 Ah each) are selected. To test the performance of the PLC control, PLC S7-1200 and KTP700 Basic HMI panel are programmed using Siemens software, TIA portal V13. Control effectiveness is tested by changing the output values (using potentiometers) of the 26 sensors, temperature, $V_{DC\ -bus}$, current levels of the 12 batteries and 12 SOC sensors. The results show a good performance of the PLC control algorithm during the charging, discharging and overheating of the batteries. This is important to ensure proper and safe BEES operation and to prolong battery lifetime.

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