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Development of a Battery Management System for Centralized Control of a Battery Cluster

Tamara Trogrlić, Mateo Beus

Summary **— The purpose of this paper is to establish a supervisory battery management system which collects active power, reactive power and state of charge measurements from the installed battery storage units and enables active and reactive power control. In addition, an HMI user interface was designed to allow the user to monitor and control the batteries. The batteries communicate with the PLC via Modbus TCP/IP protocol. The communication enables the exchange of measured power and state of charge values between the PLC and batteries, as well as setting the desired power setpoint values and battery activation signals. The PLC and HMI communicate via PROFINET. The battery storage units are installed in Smart Grid Laboratory (SGLab) at the University of Zagreb Faculty of Electrical Engineering and Computing.**

Keywords **— battery management system, Modbus TCP/IP, PLC, HMI, user interface.**

I. Introduction

At a time when the impact of electric power industry on the environment is gaining importance, new technologies are being developed to help the power system face the challenges of integrating renewable power sources into the system. An example of these new technologies which can help increase the flexibility of the existing power system are batteries, especially when used with photovoltaic (PV) systems. In that regard, the authors in [1] introduced the control strategy to achieve decentralized power management of a PV/battery hybrid unit in a droop-controlled islanded microgrid. Furthermore, the authors in [2] introduced a control strategy designed for hybrid energy storage system. In the proposed control strategy battery storage is used to compensate for slow charging power surges, while supercapacitors are applied to compensate for the fast charging surges. Additionally, in [3] the authors analyzed the configuration, design and operation of a grid with large PV penetration. In order to increase operational flexibility the proposed grid configuration also included a utility scale battery storage system connected to the grid through an independent inverter. In [4], a hybrid control strategy for PV and battery storage system in a stand-alone DC microgrid is proposed. Researchers in [5] developed a control strategy to achieve fully autonomous power management of multiple photovoltaic (PV)/battery hybrid units in islanded microgrids. The control strategy introduced in that paper had the ability to autonomously coordinate with dispatchable droop controlled units. By and large, batteries require a monitoring and control system to maximize their efficiency, but also to help re- searchers to better understand and improve existing technolo- gies. Interesting research in terms of the BMS development has been presented in [6]- [8]. In that regard the authors in [6] presented the BMS design for the application in the electric vehicles, while the authors in [7] introduced an advanced BMS for the application in smart grid infrastructure. In [8] the authors developed a hardware-in-the-loop (HIL) simulation battery model for purposes of BMS testing on a commercial HIL simulator. Additionally, in [9]- [10] the authors provided an extensive overview of the BMS designs for the application in the smart grid environment. Furthermore, the papers [11]- [12] deal with the advanced design of the BMS. In [11] the authors presented design and implementation of a BMS for the industrial internet of things (IIoT) enabled applications, while in [12] the authors presented the development of a BMS whose operation is based on the application of an Multi-Objective Gravitational Search Algorithm to schedule the best battery allocation.

Furthermore, the authors in [13] elaborated the concept of a virtual inertia provision using battery energy storage system.

This paper describes the development of a supervisory BMS (Battery Management System) application for battery units applied in households. The control algorithm is implemented using a PLC (Programmable Logic Controller), while the HMI's (Human-Machine-Interface) touch panel enables an intuitive user-friendly interface. The main goals of the designed BMS were to collect the chosen measurements from the batteries and display them on the HMI screen, and to create both active and reactive power management functions as well as SOC balancing functions. Establishing the communication between the batteries, PLC and HMI was of the utmost importance for the BMS to work. The paper is structured as follows. The established laboratory setup that is used for development of the BMS is described in the Section II. Section III provides a detailed overview of the developed BMS, from establishing communication to the designed functionalities. Experimental results are presented in the Section IV.

II. Laboratory Setup

This section gives an overview of VARTA Pulse 6 energy storage [15], SIMATIC ET200-SP PLC [18] and SIMATIC

TP1200 Comfort Panel HMI device [20]. Figure 1 illustrates the general overview of the equipment that is used to establish

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the necessary laboratory setup. As shown in Figure 1 the communication network used to establish the laboratory setup is Ethernet-based and uses Modbus TCP and PROFINET industrial communication protocols.

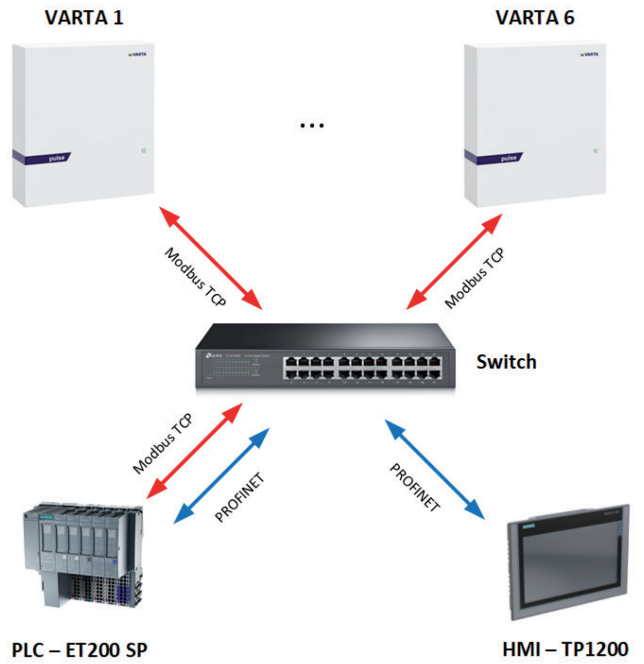

Fig. 1. General overview of the laboratory setup in SGLab

A. VARTA Pulse 6 energy storage

To explore the possibilities of energy storage systems and their monitoring and management capabilities, six VARTA Pulse 6 battery storage units were installed in the Smart Grid Laboratory (SGLab) at the University of Zagreb Faculty of Electrical Engineering and Computing [14]. Since each battery unit has a single-phase inverter, a pair of two battery units is connected in each phase in order to establish a well balanced three-phase battery storage system.

The batteries' technical characteristics are displayed in Table I.

TABLE I

VARTA Pulse 6 technical characteristics [14]

Nominal capacity	6.5 kWh
Max. AC charge/discharge power	2.5/2.3 kW
Depth of discharge	90%
Electrochemistry	NMC
Mains connection	230V AC, 50 Hz, 1-phase
Mains configuration	TT-systems, TN-systems
Max. current output	11A
Protection class	IP33
Ambient conditions	+5°C to +30°C
Recommended circuit protection	B 16A MCB

First and foremost, the described battery storage system is designed for use in households with installed PV systems to get the most out of the locally produced energy [16]. With that in mind, an electric current sensor which controls the charging and discharging is included in the battery storage system's additional equipment. The sensor is installed just after the electricity meter and monitors the electric current direction: if the direction is from the object into the grid while the battery's state of charge (SOC) is less than the maximum SOC, the battery is charged. On the other hand, if the PV energy production does not meet the object's needs, the electric current direction is from the grid into the object and the battery is discharged (if it has a sufficient SOC) with the goal to minimize the consumption of electrical energy from the grid. However, it is important to note that the above-mentioned sensor is disabled in the current laboratory setup so that the battery storage units can be controlled from an external system, such as a SCADA (Supervisory Control and Data Acquisition) system. Each battery storage unit is equipped with an Ethernet interface that was used to establish communication with the PLC via the Modbus TCP/IP protocol. Figure 2 shows the installed battery units in the lab.

Fig. 2. VARTA Pulse 6 battery units in SGLab

B. Programmable Logic Controller SIMATIC ET200-SP

SIMATIC ET200-SP station is a flexible, modular, and compact system from Siemens for various automation ap- plications. The station configuration can expand up to 64 modules, including digital and analog I/O modules [17]. I/O modules were not used for this application, since all necessary inputs and outputs are exchanged via Modbus TCP between the PLC and batteries. Using an interface module enables the communication with a central PLC if the station is used as distributed I/O [18]. The PLC has a CPU 1512SP-1 PN module with the functionalities of a Siemens S7-1500 series CPU [19]. The module has a 3-port PROFINET interface. Ports 1 and 2 require a bus adapter, while port 3 has an integrated RJ45 socket. The CPU module needs a 24V DC power supply and has a reverse polarity protection. A server module, which serves as an electrical and mechanical con- nection to the backplane bus and enables the monitoring of power supply voltage, is added to the CPU module. The CPU allows for up to 4000 defined blocks, which include Data Blocks (DB), Function Blocks (FB), Functions (FC), and Organizational Blocks (OB). The developed BMS algo- rithm uses two Organisational Blocks (OBs). The first OB1

- Main (contains Functions (FCs) which output final active and reactive power setpoints and activation signals) and OB30

- Communication (contains configured Modbus Clients and power monitoring functions). The block Main is executed with each PLC cycle, while Communication is a cyclic interrupt block which executes every 100 ms. Cyclic interrupt is used since the measured values don't change rapidly and such a delay in sending setpoint values to the batteries is insignificant. The FC's in Main use auxiliary FC's responsible for smaller tasks, such as a FC used for SOC regulation which checks the SOC of a battery and determines the corresponding power setpoint. Data Blocks (DBs) are

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used to organize measured and calculated data, as well as parameters needed for Modbus clients. The PLC supports following programming languages (IEC 61131-3): LAD (Ladder Diagram), FBD (Function Block Diagram), STL (Statement List), SCL (Structured Control Language) and GRAPH. LAD programming language was used for programming the BMS application in the PLC. The CPU supports various communications protocols, such as IP protocol, PROFINET IO, Open IE communication, OPC UA and Modbus TCP. It can have up to 128 simultaneously active connections, including those connected either via the CPU's integrated interfaces or via the communication processor mod- ule. Furthermore, the PLC can be connected to the Human – Machine Interface (HMI) via PROFINET to allow the user to easily control and monitor the battery storage units by means of a graphic user interface, which will be discussed later. The connection is created in the *Devices and networks* window of TIA Portal by connecting the Ethernet ports of the PLC and the HMI. The PLC and HMI are then in the same subnet. Their IP addresses must be set accordingly. In addition to having unique IP addresses, the devices communicating via PROFINET also need to have unique PROFINET device names.

C. SIMATIC TP1200 Comfort Panel

The chosen HMI device for this application is a SIMATIC TP1200 Comfort Panel from Siemens, which is designed as a touch screen. It has a TFT (thin-film-transistor) display, which is an LCD (liquid-crystal display) variant, with a 12.1-inch screen diagonal [20]. Control elements include only numeric and alphanumeric onscreen keyboards, but can be expanded with up to 40 direct keys (touch buttons). The required supply voltage is 24V DC, with a permissible range between 19.2V and 28.8 V. The panel has an x86 type processor, Flash and RAM memory, and 12 MB available memory for user data. It comes with a pre-installed Windows CE operating system. The panel is equipped with a 2-port industrial Ethernet interface, one RS-485 interface and two USB 2.0 interfaces. The supported protocols include PROFINET, PROFIBUS, EtherNet/IP, MPI, IRT and PROFINET IO. HMI can be configured from TIA Portal, using either a WinCC Comfort, WinCC Advanced or WinCC Professional software. There is a message system with 32 alarm classes and configurable acknowledgement groups. In addition, recipe management is a particularly interesting functionality for industrial automation. The HMI can be used for process monitoring and control in combination with PLCs from manufacturers other than Siemens, such as Allen Bradley and Mitsubishi. Laboratory setup used for testing is shown in Figure 3. It consists (from left to right) of a 24V DC industrial power supply, the PLC, a network switch, the HMI and a laptop. The power supply powers the PLC and HMI. The PLC, HMI, batteries and laptop are connected to the switch using Ethernet cables so that they are in the same LAN network. The HMI's main screen (with default values, before reading the battery measurements) is displayed in Figure 4. It shows the batteries as icons and displays the measured active, reactive and apparent power values, as well as the SOC for each battery. Total active, reactive and apparent power values can be seen at the bottom of the screen. A drop-down menu for choosing the screen for different control mode (active/reactive power control and SOC control) can be seen in the bottom right corner.

There are separate screens for active power/SOC regulation and reactive power regulation, but their working principle is the same. First and foremost, a management function variant must be selected on the screen. Once it is selected, the corresponding input fields and switches appear on the screen. The screen allows manipulating the inputs of the selected func- tion only. If the selected active power management function changes, all battery units are deselected to prevent them from accidentally following another management function's outputs. However, if the selected reactive power regulation function changes, all reactive power setpoints are just reset to zero, to avoid affecting the battery unit selection of active power management functions.

To finish connecting the HMI with the PLC, a connection has to be created in HMI's *Connections* tab in the TIA Portal. The connection parameters include the interface type and the devices' IP addresses. The created connection is later used to link the HMI tags with the corresponding PLC tags. Objects, such as I/O fields, buttons and text fields, are added to the screens using drag-and-drop and linked to HMI tags. Layers were used to reduce the number of screens. Screen objects that belong to the same function were arranged in the same layer and their visibility was set so that they are visible only when that function is selected. The HMI collects user-controlled inputs which get forwarded to the PLC. The PLC performs the programmed logic using these inputs and sends the necessary outputs to the HMI so the process can be monitored by the user.

D. Modbus TCP/IP communications protocol

Modbus is a communications protocol developed in 1979 by the Modicon company. It is widely used in industrial automation thanks to its simplicity and flexibility. Master/slave is main working principle of the Modbus RTU or client/server in case of Modbus TCP. Slave devices receive data from or send data to a master device only upon getting a request from a master device. Slave devices cannot volunteer data. Every device communicating via Modbus is required to have

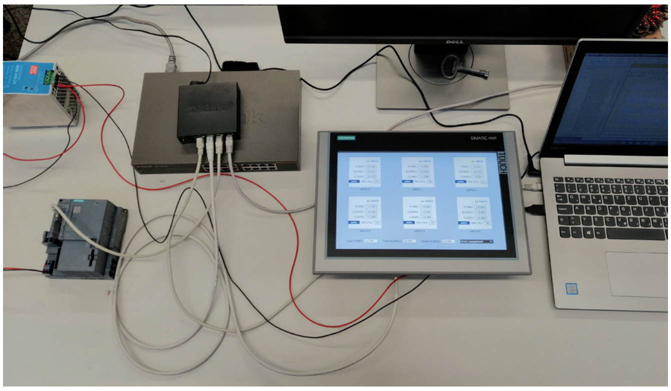


Fig. 3. Laboratory setup for BMS testing

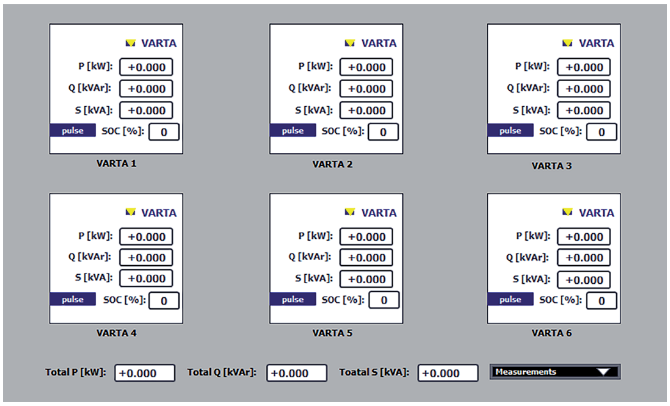


Figure 4. HMI main screen of developed BMS

a unique address. The most common variations of the Modbus protocol are Modbus RTU, Modbus ASCII, and Modbus TCP. Modbus RTU and Modbus ASCII are serial protocols which use a RS-232 or RS-485 interface, while Modbus TCP follows the OSI network model and can be used over the Ethernet infrastructure.

Another difference is that when using Modbus RTU and Modbus ASCII, there can be only one master device in the network, while Modbus TCP allows for multiple servers accessed by multiple clients. To use Modbus TCP, IP addresses of all devices in the network must be known. Modbus client device sends data to port 502 on server devices. Server device register types are listed in Table II [21].

TABLE II

MODBUS REGISTER TYPES

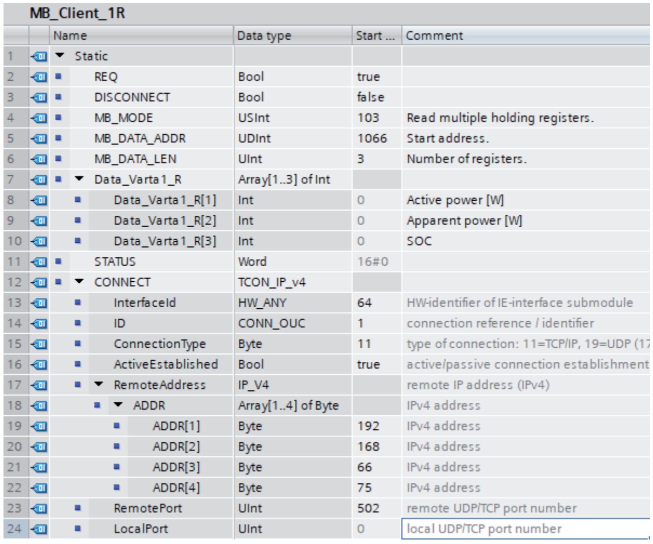
Memory block	Data type	*Client* access	*Server* access
Coils	Bool	read/write	read/write
Discrete inputs	Bool	read-only	read/write
Holding registers	Word	read/write	read/write
Input registers	Word	read-only	read/write

Address spaces for the above-mentioned memory blocks are: 00001-09999 for coils, 10001-19999 for discrete inputs, 20001-29999 for holding registers and 30001-39999 for input registers. The first digit of the address area determines the type of the register, and the remaining digits its location. Every Modbus command contains the address of a slave device that needs to be accessed, and a checksum to detect transmission errors. Modbus register table must be given for a device to know the addresses of its registers and what they stand for. In addition to the above, Modbus commands also contain Modbus function codes which define the desired action for the addressed register. Modbus functions can be regarded as either read or write functions and can moreover be differentiated by the type of the register being accessed. For example, the function code 3 stands for reading multiple holding registers. Exception codes are defined to help find the problem in case of a failed communication.

III. THE DEVELOPED BMS APPLICATION

A. *ESTABLISHING COMMUNICATION OF THE PLC WITH THE BATTERIES*

Successfully establishing the communication of the PLC with the batteries and the HMI is the first step to creating a battery management system. The PLC communicates with the battery storage units via Modbus TCP protocol over an Ethernet network. It enables retrieving the following mea- surements from the batteries: active power, apparent power, and state of charge. Furthermore, it enables sending the active and reactive power setpoints, along with an on/off signal, to the batteries. The absolute value of reactive power for each unit is calculated from the active and apparent power because the dedicated Modbus register for its measurement does not exist in the battery storage units. PLC acts as a Modbus client device, while the batteries have the role of a Modbus server. To establish a connection between the PLC and a battery storage unit, an already existing system function block in TIA Portal, called MB CLIENT, was used. One MB CLIENT represents one connection, and every connection needs a separate ID. Ev- ery battery needs separate connections for read and write func- tions because Modbus mode (MB MODE), which includes the Modbus function code, is an input to the MB CLIENT function block. Input parameters also include data address and data length, which together determine how many registers to read, starting at the given address, set according to the Modbus register table of the batteries. MB CLIENT needs a memory location for saving the acquired data or from which to send the data to the battery. Request and Disconnect parameters define if the communication requests are being sent and if the connection with the device is established, respectively. The last important input parameter is Connect, which contains the PLC's hardware-defined Ethernet interface ID, the connection ID, connection type, the requested device's IP address and the port number on the battery unit [22]. A separate data block was created for each connection, and it contains the described parameter configuration for the respective connection, along with an array in which the read data is stored or from which the data is written to the battery. An example of a data block with the above-mentioned parameters is given in Figure 5. That data block configures the connection for reading the data from the first battery. In total, 18 connections were created, 6 of which are used for reading the measurements, and the rest are used for writing power setpoints and on/off signals (since the reactive power setpoint register is not positioned



MB_Client_1R

	Name	Data type	Start ...	Comment
1	Static			
2	REQ	Bool	true	
3	DISCONNECT	Bool	false	
4	MB_MODE	USInt	103	Read multiple holding registers.
5	MB_DATA_ADDR	UDInt	1066	Start address.
6	MB_DATA_LEN	UInt	3	Number of registers.
7	Data_Varta1_R	Array[1..3] of Int		
8	Data_Varta1_R[1]	Int	0	Active power [W]
9	Data_Varta1_R[2]	Int	0	Apparent power [W]
10	Data_Varta1_R[3]	Int	0	SOC
11	STATUS	Word	16#0	
12	CONNECT	TCON_IP_v4		
13	InterfaceId	HW_ANY	64	HW-identifier of IE-interface submodule
14	ID	CONN_OUC	1	connection reference / identifier
15	ConnectionType	Byte	11	type of connection: 11=TCP/IP, 19=UDP (17
16	ActiveEstablished	Bool	true	active/passive connection establishment
17	RemoteAddress	IP_V4		remote IP address (IPv4)
18	ADDR	Array[1..4] of Byte		IPv4 address
19	ADDR[1]	Byte	192	IPv4 address
20	ADDR[2]	Byte	168	IPv4 address
21	ADDR[3]	Byte	66	IPv4 address
22	ADDR[4]	Byte	75	IPv4 address
23	RemotePort	UInt	502	remote UDP/TCP port number
24	LocalPort	UInt	0	local UDP/TCP port number

Fig. 5. MB CLIENT configuration parameters

immediately after target power and on/off signal registers, it cannot be simply written using the same MB CLIENT). Finally, all MB CLIENT blocks are gathered in a dedicated function in the cyclic interrupt block OB35, which is executed every 100 milliseconds.

B. *BATTERY MANAGEMENT FUNCTIONS*

The main purpose of this paper was to create the BMS and its corresponding HMI application. On the HMI's main screen, the battery storage units are represented as icons showing their respective active power, reactive power, apparent power, and state of charge measurements. The main screen also includes the batteries' combined active power, reactive power, and apparent power measurements.

1) Measurement acquisition and display: Measurements are acquired every time the OB35 cyclic interrupt block executes and are saved in their predefined memory locations. Since the power is measured in watts, but has to be displayed in kilowatts, an additional function was created to modify the acquired measurements. The function also calculates the batteries' reactive power, as seen in Equation 1, where Q_i is the *i*-th battery's reactive power in kilowatts while S_i and P_i are the *i*-th battery's apparent and active power in watts, respectively.

$$Q_i = \frac{\sqrt{S_i^2 - P_i^2}}{1000} \qquad i = 1, .., 6 \qquad (1)$$

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Reactive power sign is afterwards determined from the sign of the input percentage in reactive power regulation function. In addition, the same function is used to calculate the combined active power, reactive power, and apparent power values for display on the HMI's main screen. There is one HMI screen dedicated to the trend view of measured values and some setpoint values. It allows the user to select whether he wants to see active power, reactive power or SOC values by pressing the onscreen buttons. It also shows the user which management functions are selected, so the user knows which values to focus on.

2) Management functions: The BMS consists of three main management functions: active power regulation, which has two variants, SOC regulation with two variants and reactive power regulation, which also has two variants. Functions have their dedicated screens, where the user can select the management function variant and input the desired setpoints though the HMI's touch screen. Moreover, active and reactive power regulation should theoretically be able to operate indepen- dently, but it was found during laboratory testing that for reactive power regulation to work properly, the selected battery unit's active power setpoint must be different than zero (in other words, the batteries cannot have a solely reactive power output).

3) Active power regulation: Active power regulation has the following variants:

- Unit active power regulation: each battery unit's active power setpoint is set separately
- Group active power regulation: one active power setpoint is divided amongst the battery units

There is a dedicated function in the PLC which gathers all the necessary inputs for all variants, but only executes the code designed for the selected variant. The outputs of the function are final active power setpoints (integer value, in watts, as is required by the battery units) that are sent to the batteries via Modbus TCP, using the configured Modbus clients. The batteries have internal regulators which correct the setpoints if they are out of the allowed range.

Unit active power regulation allows the user to set a different charging (positive value) or discharging (negative value) power setpoint for each battery, as well as to turn the battery on or off. Active power setpoints are set through the HMI's input fields, while the on/off functionality is implemented as a switch. Input fields and switches (for all described functions) are connected to the HMI's corresponding tags, which are in turn connected to the PLC tags. These tags are inputs to the dedicated function in the PLC. That function takes care of making the necessary adjustments to the inputs, such as converting the data type and unit of measurement (kilowatts to watts). The HMI screen which enables the described unit active power regulation is shown in Figure 6.

Group active power regulation enables the user to input a sin- gle active power setpoint (either a positive or a negative value), which then gets equally divided amongst the six batteries. All battery units are activated or deactivated simultaneously using one switch on the HMI screen. The PLC function calculates the setpoint which gets sent to the batteries and once again makes the necessary adjustments.

4) SOC regulation: State of charge regulation is designed as follows:

- Unit SOC regulation: each battery unit's state of charge setpoint is set separately
- Group SOC regulation: all battery units get the same state of charge setpoint

SOC regulation is handled by the same function as active power regulation since it ultimately modifies active power

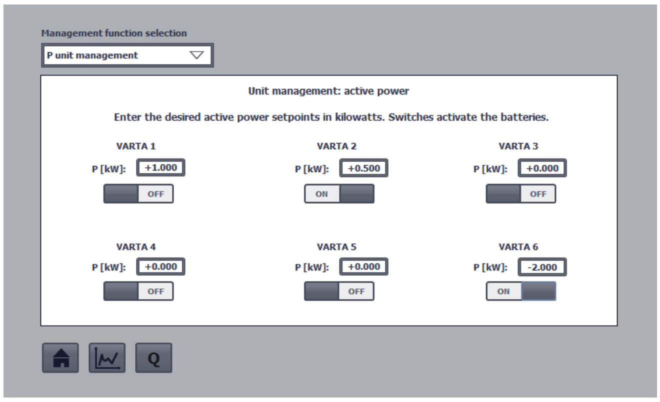

Fig. 6. Unit active power regulation HMI screen

setpoints.

Unit SOC regulation is focused on separately setting the desired state of charge setpoints (from 0% to 100%) for the batteries. The batteries are selected (but not activated or deactivated) via the already described switches. The algorithm is as follows: the function subtracts the selected battery's measured SOC from the SOC setpoint and takes the absolute value of the result. Active power setpoint magnitude is picked from four predefined values, shown in Table III, based on the calculated result (if the result is not zero). Greater SOC

TABLE III

CHARGING/DISCHARGING POWER VALUES DEPENDING ON THE SOC DIFFERENCE

/ΔSOC/ [%]	Charging/discharging power [W]
[50, 100]	2000
[30, 50)	1500
[10, 30)	1000
[0, 10)	500

difference results in a greater active power setpoint magnitude. If the measured SOC is greater than the SOC setpoint, the active power setpoint is sent to the function output as a negative value (discharging). If the measured SOC is lower than the SOC setpoint, the active power setpoint is sent to the function output as a positive value (charging). After the power setpoint is determined, the function output for battery activation is set accordingly. The outputs are sent to the battery units. This algorithm is repeated, adjusting the power setpoint as the battery charges or discharges, until the measured SOC matches the SOC setpoint or until the battery gets deselected. Then the power setpoint is 0, and the battery is deactivated. Group SOC regulation is very similar to Unit SOC regulation, the difference being that the same SOC setpoint is given for all batteries and all batteries are selected simultaneously. Determining the individual battery's active power setpoint and activation signal follows the same logic as described above.

5) Reactive power regulation: Reactive power regulation has the following variants:

- Unit reactive power regulation: each battery unit's reac- tive power setpoint is set separately
- Group reactive power regulation: one reactive power setpoint is divided amongst the battery units

As stated before, reactive power regulation requires the target battery storage unit to have an active power setpoint different than zero. There is a dedicated PLC function, which collects necessary inputs for both variants, but executes only the code needed for the selected variant. The function outputs are reactive power setpoints that are sent to the batteries via Modbus TCP.

Unit reactive power regulation enables the user to set a different reactive power setpoint for each battery. As opposed to the active power setpoints, reactive power setpoints must be set as a percentage of the rated power value, in a range [- 100%, 100%] for capacitive and inductive power, respectively. After ensuring that the input value is within limits, it gets forwarded to the output. Conversion of the set percentage into actual reactive power value is handled by the internal battery regulator and as such cannot be manipulated any further.

Group reactive power regulation allows the user to input a desired reactive power percentage setpoint, which then gets equally divided amongst the six battery units. The described functionality is shown by a flowchart in Figure 7. It must be noted that the sign of the input percentage is used to determine the sign of the reactive power value displayed on the main screen icons, since the batteries' displayed reactive power is not measured, but calculated from the apparent and active power values. Reactive power regulation is important because

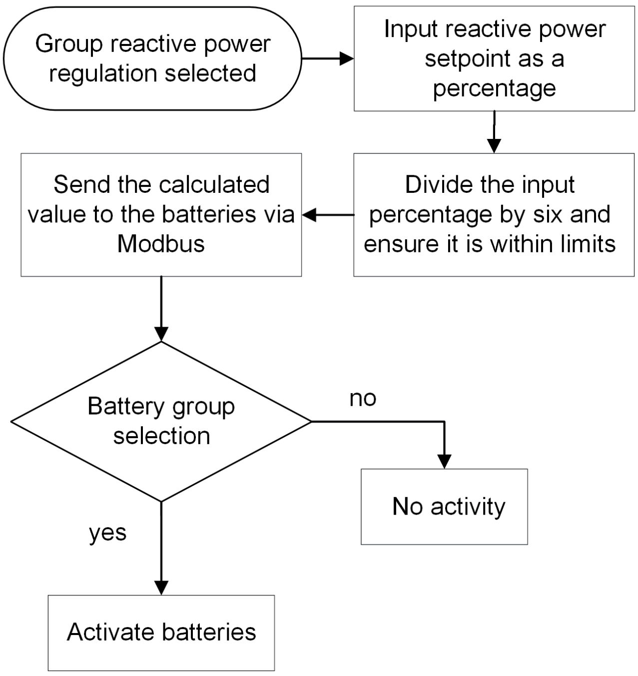

Fig. 7. Group SOC regulation flowchart

it enables voltage regulation using the battery units. Further insight into that functionality is beyond the scope of this paper.

6) Activating and deactivating the battery storage units: Since all management functions manipulate the activation and deactivation of batteries, an additional function was created to take all those influences into account. The function in- puts include the management function selection, HMI screen switches, and the on/off outputs of Unit SOC regulation and Group SOC regulation functions. The function contains a logic designed to determine whether a battery should be activated or not. The function's outputs are on/off signals for the batteries and are written to the batteries' respective registers via Modbus TCP.

IV. Experimental Results

The application was tested in SGLab using the described setup. The responses of the battery units to Group active power regulation and Group SOC regulation were recorded using TIA Portal's Trace functionality. Responses were plotted using Matlab. Figures 8 and 9 show the responses.

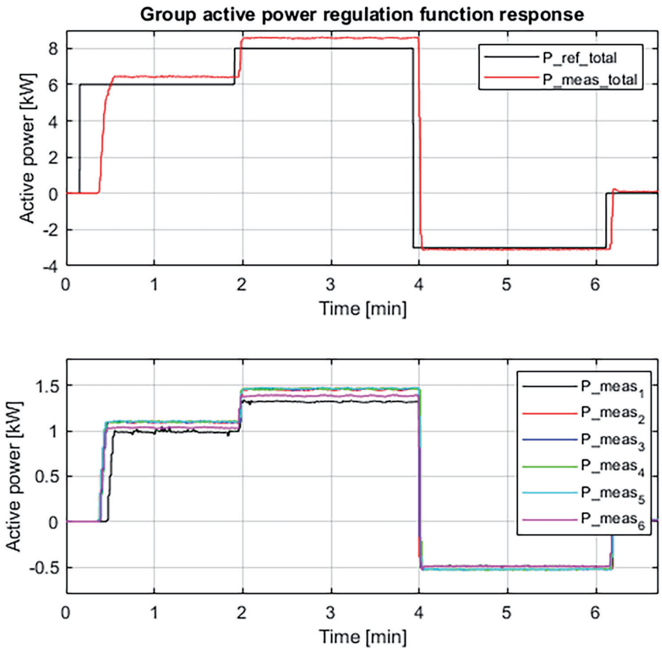

Fig. 8. Group active power regulation function response

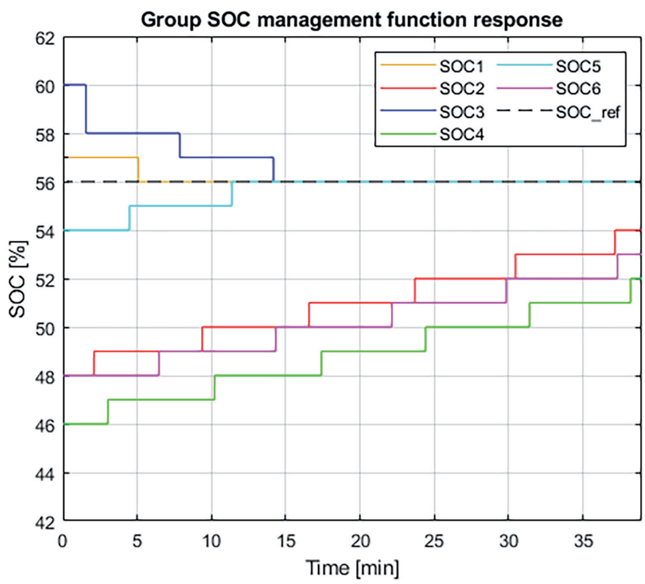

Fig. 9. Group SOC management function response

The first subplot in Figure 8 shows how the measured total active power follows the combined active power setpoint. The measured value varies slightly from the setpoint value because the internal controllers of the battery units can not precisely follow the setpoint value. The second subplot shows the distribution of the total measured active power amongst the batteries.

Figure 9 shows each battery's response to the Group SOC management function. The SOC setpoint is set to 56% for all batteries. Each battery initially had a different SOC value. It can be seen from the plot that the battery units 1, 3 and 5 reached the desired setpoint during the recorded interval, while the battery units 2, 4 and 6 are approaching the setpoint value.

V. Conclusion

This paper presents a battery management system developed for the six VARTA Pulse 6 battery storage units located in SGLab at the University of Zagreb Faculty of Electrical Engineering and Computing. The BMS was developed as a PLC application and enables monitoring and control of the installed batteries. Furthermore, an HMI user interface was created for the BMS. The user interface displays measurements obtained from the batteries and allows the control of the battery units through the HMI's touch panel. The introduced laboratory setup meets the set goals and can serve as a basis for the development of the voltage control algorithms or energy management systems that can be applied in low-voltage microgrids.

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