Smart Battery Management System for Enhancing Smart Micro Grid Performance and Energy Management

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Abstract Energy storage system (ESS) is an essential component of smart micro grid for compensating intermittent renewable generation and continuous power supply. Batteries are most commonly used in ESS. For optimal energy management of micro grid, the optimization algorithm needs knowledge of battery parameters like state of charge (SOC), voltage, temperature etc. Further for implementing various control and stability strategies, there is need of communication of battery parameters among various components of micro grid. With knowledge of battery parameter, grid operator can make better utilization of available ESS resources and also reduce renewable curtailment. A smart battery management system (BMS) is developed which calculates and communicates battery parameters. Various communication protocols namely Modbus, CAN, Ethernet and Wifi are incorporated in the smart BMS which makes it compatible for many applications. Smart BMS additionally performs active cell balancing using cell to cell balancing topology. The BMS is successfully implemented in a smart micro grid in India and the findings of the implementation are discussed in this paper. They serve as the foundation for further implementation of optimal energy management in the smart micro grid for minimizing operation costs.

Keywords Smart micro grid · Battery management system · Optimization · Energy management system

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R. K. Pillai et al. (eds.), *ISUW 2019*, Lecture Notes in Electrical Engineering 764,
https://doi.org/10.1007/978-981-16-1299-2_5

1 Introduction

The growing environmental concerns and depleting reserves of fossil fuels has led to an increase in penetration of renewable generation [1]. It is leading to an increase in Distributed Generation (DG) such as photo-voltaic, wind turbine, diesel/gas generator, etc. in the grid. The traditional grid needs to be upgraded for handling these DGs. Decreasing prices of renewable generation has increased micro grid installations worldwide. Micro grids (MG) are seen as a solution for large scale integration of DG in the distribution systems [2]. Micro grids are often resorted to for supplying remote areas where gird cannot reach [3]. Micro grids are being increasingly used for electrification in developing countries, where many area still do not have access to reliable electricity.

Micro grid mainly consists of distribution network made up of electrical loads, DGs (predominantly solar and wind generation) and energy storage systems capable of operating autonomously in stand alone mode or with grid connection [4]. MG offer benefits including higher efficiency, enhanced compatibility, increased reliability, lower environmental impact and solution for growing demand [5]. MG management is a challenging task due to the intermittent nature of renewable generation and an increase in dynamic loads in system. For enabling maximum efficiency of energy utilization, renewable generation is normally controlled with maximum peak power tracking algorithms [6]. Also, it is a non-dispatchable generation due to the fast changing and uncontrollable nature of weather conditions. The presence of non-dispatchable generation and varying load demand lead to issues in active power balance of load, generation and energy storage. The operation of micro grid is thus controlled with an Energy Management System (EMS) which ensures its reliable, secure and economical operation in both grid-connected or stand-alone mode [4].

With advancement in information and communication technology grids are becoming smarter. Smart micro grid enables secure and optimal operation of potentially islanded system. But for implementing smart micro grid control strategies like EMS, there is a need of communication between components of micro grid [4]. A number of communication protocols are employed in a MG and components of MG must be equipped with required communication protocol for being compatible to operate in MG. Sensors send data to Intelligent Electronic Devices (IEDs) which issue control commands to components of MG. The MG controller may use Modbus compliant with IEC 61850 standard for communicating over Ethernet using TCP/IP. Employing internet communication protocol suite, a secure and reliable communication between components of MG can be ensured. Human Machine Interface (HMI) clients are also expected to be used for monitoring and controlling requirements, additionally a data logging server and an event recorder is also expected. Figure 1 illustrates the data flow between the microgrid components.

IEDs receive power system data from DGs, ESS and load which is transmitted as feedback to MG controller. This data is utilized by MG controller for issuing control signals and reference values of voltages, frequency, active and reactive power to IEDs. IEDs consequently provides control signals to DG, ESS and load.

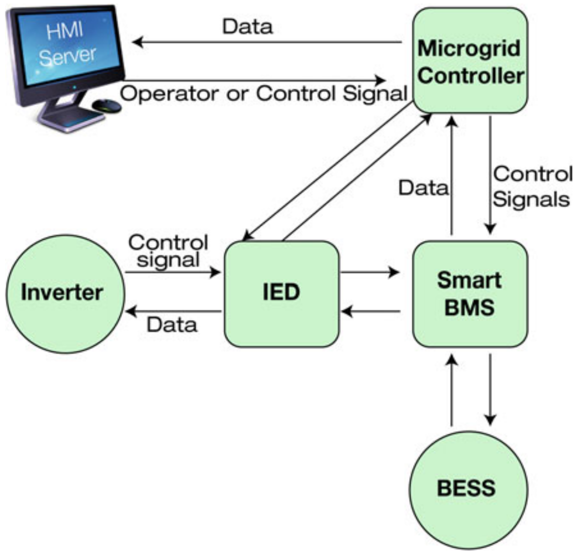


Fig. 1 The data flow between the microgrid components

Energy storage system (ESS) is an essential component of smart micro grid for compensating intermittent renewable generation and continuous power supply. It reduces need of diesel generation in micro grid and helps in optimizing the cost of operation. ESS is implemented with many different technologies like pumped hydro, fly wheels, batteries, capacitors etc. Battery energy storage systems have been found most suitable for micro-grid considering their efficiency, energy density, response time, discharge duration, depth of discharge, lifetime cycle capacity, etc. [7]. Batteries are made up of cells and each cell needs to operate within its safe operating limits for the battery to have long life. A Battery management system (BMS) ensures safe and optimal operation of batteries. In this paper a smart BMS is developed for using battery energy storage in a smart microgrid.

2 Battery Management System

The performance of battery depends on the chemicals inside the battery. With time and usage the chemicals in battery undergo degradation and the energy storage capacity of battery also reduces. The battery charging and discharging profile needs to be controlled under various load conditions for curtailing the battery depreciation process [8]. Operating conditions like frequent charge and deep discharge cycles, wide range of operating temperature and high current pulses on battery diminishes its life. Now-a-days, Li-ion chemistry is being preferred due to its good energy density, long life, efficiency and high power rating. Li-ion chemistry being very sensitive to overcharges and deep discharges need a proper BMS for safe and reliable operation of each cell.

In addition to basic function of battery protection, the BMS needs to determine status of battery as well, in order to provide information about its energy supply and absorption capacity to the MG controller. This task of determining battery status is challenging, since the usable capacity and internal resistance of battery varies over time [9]. Another crucial function performed by BMS is cell level balancing for enhancing life of battery.

A. Battery Parameter

Cells in a battery rarely have equal capacities. This causes a mismatch in state of charge (SoC) of cells while charging and discharging. Battery protection system needs to stop charging or discharging as soon as even a single cell reaches its minimum and maximum SoC limit. However, due to this all cells might not reach their full state of charge. It is often found that cells with higher voltage have higher SoC. Mismatch in cell SoC affects the performance of battery. The battery protection circuit stops battery charging before reaching its full charge voltage due to any one cell reaching its maximum SoC. Similarly, during discharging the battery stops discharging even before reaching its maximum discharge limit. Mismatch in cell capacities is the cause of underutilization of battery. It needs to be addressed with appropriate cell balancing technique for improving the utilization capacity of battery and its cycle life [10]. BMS performs the function of cell balancing along with protection of battery.

BMS needs majorly battery current, voltage and temperature measured over time as input. Using these inputs the BMS performs battery protection and estimation of battery state of charge (SoC), state of health (SoH) and state of function (SoF). Additionally, it also performs the tasks of controlling the heating/cooling subsystem and main power switch. It also ensures the isolation from high voltage when used in high voltage application by implementing isolated communication.

Another requirement from BMS is that of meeting accuracy and synchronization of current and voltage measurements of the battery pack and its cells. Accuracy targets for current measurement up to 140 A are typically 0.5–1% and 1–2 mV or 0.1% in case of cell and pack voltage measurements. Such stringent voltage accuracy demand is mostly driven by $LiFePO_4$ chemistry. Since, it has very flat voltage versus state-of-charge profile which make it difficult to estimate SoC in 80–20% range.

The accuracy of BMS measurement is affected by error sources such as variation in shunt resistance, amplifier gain and Analog-to-Digital Converter (ADC) reference over temperature and time. The BMS accuracy must be maintained since recalibration normally is not a feasible option. Accurate predictions over lifetime can be achieved with comprehensive qualification tests. Biased high temperature operating conditions which cause pre-aging in electronics also need to be considered for maximizing long term accuracy.

B. BMS architecture

BMS architecture depends on physical structure of battery used. High power application requires over one hundred cells to be connected in series. Normally modules consisting of 4–16 series connected cells are combined to form the higher voltage string of cells. Thus, battery can be viewed as three layer structure namely the elementary cell, the module and the overall pack. The inner most layer is of cell monitoring with Cell Monitoring Unit (CMU) for each cell in the module. The middle layer comprises of Module Management Unit (MMU) one for each module. The monitoring data from CMUs in module is used by MMU for providing services to the Pack Management Unit (PMU) whose function is to supervise all the modules. Each CMU can be connected to each MMU using a dedicated and custom bus. Normally communication between PMU and the MMUs is implemented using Serial Peripheral Interface (SPI) or a shared galvanic-isolated Controller Area Network (CAN) bus. Furthermore, the communication between battery and other control systems like inverters etc. is also normally using CAN bus.

Battery is protected against overcharge, deep discharge and over-temperature usually by breaking the battery current flowing through the Main Switch (MS) contactor/High power Relay. This is also controlled by the Smart BMS.

C. Battery Balancing

Battery balancing, one of the most important function of BMS, can be performed with a number of approaches. In passive balancing technique, excess energy in a cell with higher SoC is dissipated in bleeder resistor. This method is inefficient as it wastes energy in bleeder resistor which also causes increase in temperature. Active balancing technique on the other hand transfers energy from the cell with higher SoC to a cell with lower SoC which makes it more efficient than passive balancing. There are different methods of energy transfer between cells in active balancing techniques. However, for making active balancing preferable over passive balancing, a trade-off between complexity of active balancing circuit and its efficiency needs to be found. Passive balancing technique can be easily implemented using just one controlled switch and a resistor. MMU includes the hardware implementation of charge equalizer whereas supervising the overall balancing procedure is done by PMU. It estimates the SoC of each cell and controls the amount of charge to be stored in it. However, as battery capacity decreases with time, aging effect needs to be taken into account for accurate SoC estimation.

One of the method of estimating SoC is by coulomb counting assuming capacity of cells is known. Coulomb counting is performed by integrating the battery current over time. It is usually used in low power applications like portable consumer devices. Coulomb counting method is affected by measurement errors particularly in current sensor. Using relation between SoC and open circuit voltage (OCV) is another method of estimating SoC. In this method errors get introduced with error in OCV measurement due to its dependence on accurate OCV. Other methods like discharge tests, neural networks, internal resistance measurement are also available [11]. Model-based algorithm (like Kalman filters) are found to be more suitable for online SoC estimation [12]. Since it does not requires long tuning times. However, an accurate cell behavior model over its life time also needs to be developed for model-based methods. Temperature effects must also be considered while modeling the cell behavior [13].

3 Smart Battery Management System

The smart BMS developed in this work is used for monitoring 48 V battery containing 16 $LiFePO_4$ cells as shown in Fig. 2. It determines individual cell voltage, current, temperature, SoC and SoH. It protects the cells against overcharge, over discharge, over current, over temperature and short circuit. It is also possible to set depth of discharge and charge levels of the battery. It works as MMU in high voltage packs for up to 128 cells in series and one of the BMS acts as both MMU and PMU.

The smart BMS supports active cell balancing and is capable of balancing cells within a single module and also in different modules. It supports CAN bus communication which makes it compatible with inverters commercially available.

Fig. 2 Smart BMS connected to Li-Rack battery

4 Smart Microgrid in India

A smart MG is installed in Goa in India which comprises of 10 kWp solar generation, battery energy storage system (BESS) of 11.2 kWh, diesel generator of 10 kW, load and utility grid. The developed smart BMS is implemented in this MG successfully. The ethernet port on the smart BMS enables monitoring the battery energy storage and controlling its working as well. It can be paired to a SCADA system using MOBDUS protocol over ethernet port. Further, pairing to Wifi network though ethernet port is also possible. The MG controller can control the battery energy storage by communicating with the smart BMS. The inverter used in MG is also smart inverter and is capable of being controlled by MG controller and battery. Thus, using MG controller it is possible to implement optimal management of energy for minimizing operating costs of MG.

5 Energy Management System for Minimizing Operating Cost of Microgrid

The supply of grid is unreliable and battery energy storage or diesel generation is used to supply the load while it is unavailable. The cost of energy generated by a diesel generator is higher than grid supply. Hence, it is economical to use BESS during outage as compared to diesel generator. Also, solar generation is installed which further reduces the cost of operation. The presently used EMS is Rule-Based, wherein solar generation is priority and is used for supplying load with BESS and grid. Proportion of grid supply in total power to MG increases as solar generation reduces. In absence of solar generation load is supplied with utility grid. For backup, the battery SoC is maintained around 90%. During grid outages and absence of solar generation, BESS is used to supply the load and when BESS SoC reaches minimum limit, diesel generator supplies the load.

The battery is charged back to 90% when utility grid supply is available again. The data of MG operation on a random day are displayed in graphs in Figs. 3, 4, 5 and 6.

Readings obtained from smart MG reveals that the solar generation is wasted, if it is more than load and battery is also fully charged. Daily average energy which solar panel can generate is found to be 40 kWh of which an average of 22 kWh of energy is utilized. BESS needs to be at lower SoC for storing the excess solar generation. Whereas, for minimum use of diesel generation during grid outage, battery needs to be maintained at full SoC. Thus, EMS needs to maintain optimal SoC for minimizing use of diesel generation and maximizing use of solar generation. Optimal operation of MG is achieved by minimizing the consumption of energy from diesel generation and grid.

In this system, solar generation is assumed to be free of cost. Charges need to be paid for using energy from grid and diesel generator. A day-ahead forecasting of

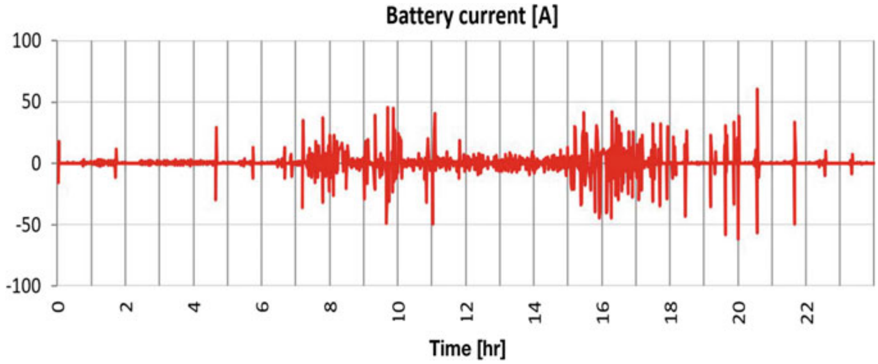
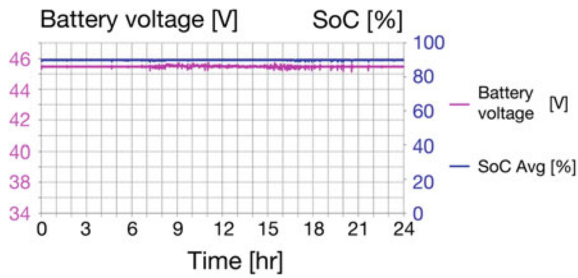


Fig. 3 Battery current

Fig. 4 Battery voltage and SoC



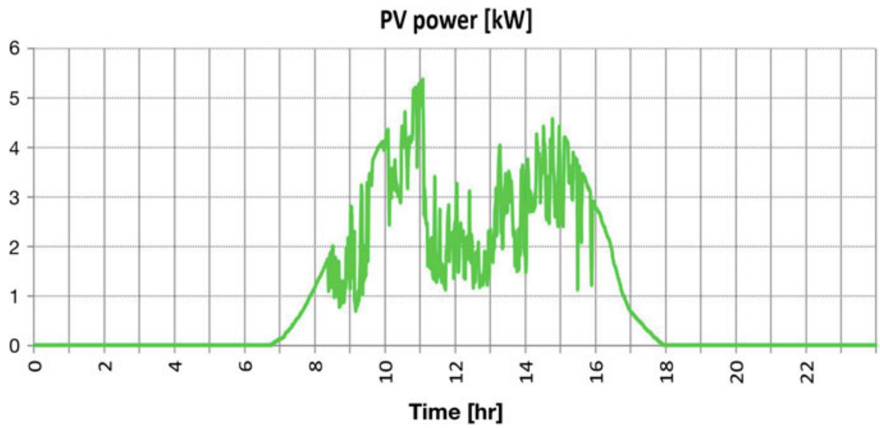


Fig. 5 PV power consumed by load

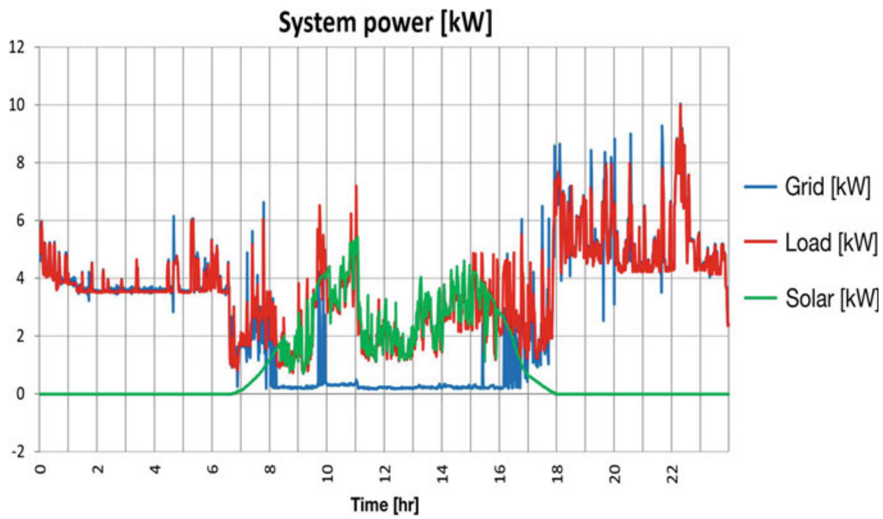


Fig. 6 System power

load and solar photovoltaic (PV) generation [14], is used for scheduling sources to supply load. The optimal energy management of MG can be achieved using Bellman algorithm by scheduling sources for minimizing cost of operation [15].

A. Objective Function

The total cost of operating MG for one day is denoted by Cost in (1) and the objective is to minimize the value of Cost.

$$\min(Cost) = \min \sum_{t=0}^{T} P_g(t) \cdot T_g + Dsl(t) \tag{1}$$

P_g : Utility grid power
T_g : Utility grid tariff
Dsl : Cost associated with probability of using diesel generator.

The discharging of battery increases probability of using diesel generation. $Dsl(t)$ can be calculated as product of probability of using diesel generation and cost of supplying average load with diesel generation. Thus, as battery SoC decreases value of $Dsl(t)$ increases.

The data obtained from the implemented smart MG is used for calculating probability of using diesel generation as function of time of day and battery SoC. The probability function will be updated with time to give more accurate results. Similarly, average load is also derived using the data and regularly updated with time.

B. *Constraints*

Power Balance constraints

$$P_l(t) = P_g(t) + P_B(t) + P_{PV}(t) \tag{2}$$

P_t : Load power
P_{PV} : Power supplied by solar generation
P_B : Battery power.

Battery output power

$$P_{B\text{min}} < P_B < P_{B\text{max}} \tag{3}$$

State of charge of battery can be calculated as

$$Soc = \frac{C(t)}{C_{ref}} \tag{4}$$

where $C(t)$ is instantaneous capacity of battery and C_{ref} is the reference capacity.

The SOC variation constraints are:

$$\Delta SoC_{\text{min}} < \Delta SoC(t) < \Delta SoC_{\text{max}} \tag{5}$$

SoC constraints are taken as

$$SoC_{\text{min}} < SoC(t) < SoC_{\text{max}} \tag{6}$$

Minimum SOC of 20% needs to be maintained for diesel generator to reach its full capacity while BESS supplies load. Maximum Solar generation can be of instantaneous load and BESS charging power and excess generation will be wasted.

$$0 < P_{PV}(t) < P_l(t) + P_B(t) \tag{7}$$

6 Optimisation in EMS

The MG optimization problem can be seen as Multi-Stage Decision Problem (MSDP) [16]. Each step of MSDP consists of number of system states which determine the value of current stage. On each state of a stage, a set of decision variables acts for generating new states which belong to next stage. The aim of using Bellman algorithm is to find the optimal path of state transition which minimizes summation of cost of all stages.

In the current optimization problem SoC of battery acts as decision variable. The Bellman algorithm method as proposed in [15] can be used for finding the sequence

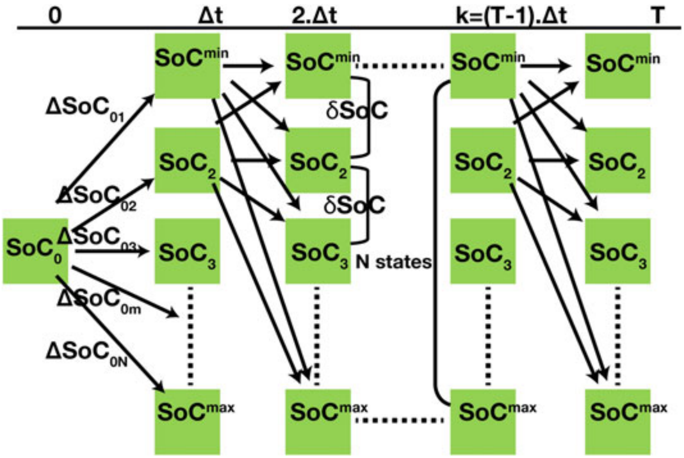


Fig. 7 Paths of SoC variation

of SoC variation in discrete steps such that Cost value is minimum. A set of variables determine the state of system at each time. The system is discretized with a time step of Δt and SoC is varied with a step size of ΔSoC [15]. At each stage, change in SoC is used for calculating the battery power (P_B) for next stage. Using calculated P_B and forecasted solar generation and load (P_l), maximum possible P_{PV} is determined. After which P_g required for maintaining power balance is inferred. And finally cost of each stage is calculated.

The initial value of SoC in the first stage is taken as the instantaneous value of SoC at the start of simulation. It is taken as source vertex for implementing Bellman algorithm. And with time step of one hour there are 24 stages remaining.

Each of the remaining stage has same number of N vertices with each vertex varying increasingly by step size δSoC from SoC_{min} to SoC_{max}. The vertices of the 2nd stage are obtained from the source vertex by adding SoC variations ΔSoC (Fig. 7). The set of vertices $\psi(1)$ which satisfy the constraints in Eqs. (2)–(7) are used for finding vertices in next stage. The value of $Cost(i, t)$ corresponding to the vertices in $\psi(1)$ are also calculated and is taken as weight of path for reaching that vertex. Using each vertex in previous stage $\psi(i)$, new vertices are obtained by adding the SoC variations (ΔSoC) and verifying whether they satisfy Eqs. (2)–(7). In this way valid vertices are found in each stage and the cost calculated at each vertex is taken as weight for path of traversing from vertex in previous stage, by which it reached current vertex. Using Bellman algorithm, minimum weight path of reaching each vertex in the last stage is found. The path with minimum weight $(\min(Cost))$ is taken as optimal path. The SoC transition along this path gives optimal day ahead schedule of sources and storage components for minimum operating cost.

Using this schedule as guide, energy management is performed by MG controller for the day and the controller simultaneously calculates optimal schedule for the next day. The implementation of this optimal energy management is possible due to features of smart BMS which enable determining status of BESS and controlling it.

Simulation parameters

Name	Value	
T	24	H
Δt	1	H
δSoC	0.001	Pu
$SoC(t_0)$	0.5	Pu
$SoC_{\min}$	0.2	Pu
$SoC_{\max}$	0.9	Pu
$\Delta SoC_{\min}$	−0.7	Pu
$\Delta SoC_{\max}$	0.7	Pu
P_{Bmin}	−11.2	kW
P_{Bmax}	11.2	kW

Thus, scheduling of sources and storage components for optimal energy management is developed and being implemented in the smart MG using the smart BMS.

7 Conclusion

The smart BMS developed in this work accurately measures and calculates essential battery parameters like battery voltage, cell voltage, battery SoC etc. It communicates the calculated parameters using CAN, Ethernet, MODBUS and Wifi communication which makes it compatible with components of smart MG, and aids the decision making of MG controller by providing accurate and appropriate data as compared to the estimations by the other devices connected to the BESS system. It also ensures operation of BESS within safety margins. The smart BMS increases the efficiency of BESS with active balancing technique. It also increases the life and performance of BESS, thereby enhancing performance of MG as a whole. This BMS is successfully implemented in a smart MG in Goa. The data communicated by the smart BMS and other components of MG, form the basis for the MG controller to implement optimal energy management. The SoC of battery is controlled for implementing optimal energy management, which is possible only due to the accurate calculation and communication of battery SoC by the smart BMS.

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