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Self-directed Energy Management System for an Islanded Cube Satellite Nanogrid

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Abstract—**This paper presents a self-directed energy management system for an islanded cube satellite Nanogrid. Since the electrical power system of a cube satellite is generally constrained in mass and volume, therefore, it offers many challenges for sustainable operation and requires efficient management of power generation, distribution, storage, and utilization. In this proposed energy management system, solar power generation is efficiently managed through an intelligent algorithm capable of interchanging its mode of operation between maximum power point tracking mode and current control mode based upon battery state of charge. The proposed control and management system not only allows the optimal solar power extraction but also tends to enhance the battery life through controlled charging. A local link is responsible for the communication of information regarding the state of charge of the battery for the smooth inter-mode transition. The proposed power electronic control system is modeled in MATLAB/SIMULINK and the results for power-sharing among solar PV, battery and load are analyzed at varying profiles of load and incident irradiance to validate the efficacy of the proposed energy management system.**

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1. INTRODUCTION

A cube satellite (CubeSat) is a miniature satellite in the shape of a cube shape used for various applications including remote sensing, space exploration, earth observation, and high-resolution imagery applications [1, 2]. These single-task satellites are available in a standard of one unit (1U) with a weight of 1.33 Kg and dimensions of 10 x 10 x 10 cm. However, the small satellite is extendable in 2U, 3U to other larger classes of satellites for greater payloads [3, 4]. The CubeSat missions were basically started as an educational tool for universities and student research. But, the recent progress and developments in small satellite technologies including fast manufacturing, higher volumetric and gravimetric densities, and cheaper cost along with the availability of innovative and affordable commercial off-the-shelf (COTS) components has drawn great attention of space venders and consumers [5].

The CubeSat comprises different subsystems including an attitude control system (ADCS), the communication link (COM), on-board data handling (OBDH) computer, payloads, and electrical power system (EPS) [4]. EPS serves as the backbone of the satellite as it powers all the other subsystems in the CubeSat. EPS is not only responsible for power generation, distribution, storage, and utilization, but it also controls the flow of power between various system components. The main source of power generation is solar photovoltaic (PV) panels, while the batteries are used to store the excess energy. This excess energy will be utilized to run the satellite operation during periods of high load and eclipse when solar irradiance is generally unavailable [4]. The load profile of CubeSat generally varies based upon the incident payloads and operational requirements [4]. The failure of EPS will not only result in the mission failure but may also lead to the overall satellite demolition. Therefore, reliability, availability, and controllability of EPS are of utmost importance for successful CubeSat missions and longevity.

Many space missions have failed due to the lack of proper coordination among the satellite components, e.g. solar array, batteries, power control units, etc. The main causes include deficiency in power bus connection with solar panels and/or batteries, power system maloperation, insufficient generated power to operate the transmitter, lack of protection from over current and voltage fluctuations as well as battery degradation [6]. EPS failure can be largely avoided using robust management strategies through controlled coordination among EPS components. In recent years, microgrid technologies have proven their potential as a candidate choice for reliable and secure electric power generation, distribution and utilization in close proximity [7,

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8]. In particular, numerous islanded microgrids have been successfully deployed for remote area electrification and telecommunication operations, where grid structure is unavailable [9-13]. The successful demonstration of islanded nanogrids with their advanced controllability, reliability, and resiliency has forced the CubeSat researchers and practitioners to consider its EPS operation as a nanogrid working in islanded mode. Therefore, this research work takes its inspiration from the control and management strategies developed for nanogrids and verifies its applicability for CubeSat EPS operation. Mashood *et al.* [10, 12] presented a solar PV based microgrid architecture consisting of a cluster of multiple nanogrids capable to interact with each other in controlled coordination. In essence, EPS of the CubeSat closely resembles the individual nanogrid architecture presented in [12], therefore, the control strategies can be successfully replicated given the environmental conditions are properly considered for the satellite applications.

In line with this argument, the coordination between the PV generation, loads, and battery storage of CubeSat nanogrid has been considered in this work. Shaliesh *et al.* [4] presented a flexible EPS controller considering PV and battery integration for 1U and 12U CubeSats. The work considers maximum power point tracking (MPPT) of the incident solar power for battery charging. The battery power is then used to drive the local CubeSat loads. Since battery overcharging leads to its state of health (SOH) and life degradation [14, 15], therefore, to avoid the overcharging, the proposed controller shift its mode from MPPT to voltage control mode with its reference equal to the battery voltage level. This will result in PV power generation lower than the load requirements as part of the incident load will be shared by the battery causing suboptimal curtailment of available solar resources and battery discharging. Alternately, a control mechanism capable to switch solar PV generation between MPPT and load power curtailment mode has been presented in this work. The proposed controller will smoothly shift its mode from MPPT to load current control; thereby will curtail incident PV power exactly equal to the local load requirements, while keeping the battery SOC at a constant level. Therefore, the poroposed control and energy management system has the capability of MPPT, curtailment according to the load requirements as well as battery life saving from excessive overcharging.

The rest of the paper has been organized as follows. Section II explains the CubeSat architecture under consideration. Section III presents the proposed control methodology along with the energy management system (EMS) and the possible modes of operation based upon the state of charge (SOC). Section IV presents the simulation results for the CubeSat case study parameters. The results are discussed for various modes of battery operation including charging, discharging and constant SOC operation. Based on the results, the conclusion is drawn in section V.

2. CUBESAT NANOGRID ARCHITECTURE

Fig. 1 shows a general architecture of the CubeSat nanogrid in which the solar panels are the main source for power generation. Generally, solar cells are placed pairwise on all the six sides of the CubeSat, such that at least three sides of the satellite remain under the sunlight during any movement other than the eclipse duration [16]. For the purpose of nanogrid analysis, we have lumped these solar cells in the form of a compact solar panel as shown in Fig. 1. A DC-DC converter is interfaced with the solar panel which is responsible for optimal power extraction from the incident irradiance and battery charging. The DC-DC converter can be a buck, boost or a buck-boost converter based upon the selection of bus voltage level, battery voltage level, and PV module characteristics. A Li-ion battery is used as a storage and is responsible for regulating the DC bus voltage. All the subsystem loads including payloads are integrated with DC bus using DC-DC converters as shown in Fig. 1. For the CubeSat system, the load profiles are generally dynamic varying from full load operation to limited mode operation. During some periods of time, the high power system is to be turned on for mission operation and therefore, CubeSat operates under full load. At other times, some of the loads are shutdown and CubeSat is working under limited functionality mode. Similarly, there are some critical loads e.g. OBDH computer and receiver that need to be powered continuously. The detailed load profile for various mission modes has been discussed in [17]. Though various loads may have different voltage requirements and DC-DC converters are needed for their operation, however, for the current scope of the work, the lumped load on DC bus has been considered without considering the details of the point of load (POL) converters. Similarly, DC bus voltage may be higher or lower than battery voltage, however, to minimize the converter requirements, DC bus voltage is generally kept equivalent to battery voltage. Based upon the incident irradiance, solar power P_S is either used for charging the battery or fulfilling the load demand P_L. When CubeSat enters the eclipse, the incident irradiance becomes zero and therefore the battery is discharged to fulfill the load demand. In a time interval Δt, an ideal energy balance neglecting the battery charge/discharge efficiency and resistive losses is given by (1).

$$P_S \, \Delta t = P_L \, \Delta t + \int_0^T V_B \left(I_S - I_L \right) dt \tag{1}$$

Where, V_B is the battery or bus voltage at which lumped CubeSat loads I_L is connected and I_S is the solar current generated and processed by DC-DC buck converter. This energy balance will help to account for the battery state of charge (SOC), based upon which control algorithm will decide its mode of operation and switching from MPPT mode to current control mode. The overall change in battery SOC in terms of its initial SOC_i and battery ampere-hour (Ah) capacity is given by (2).

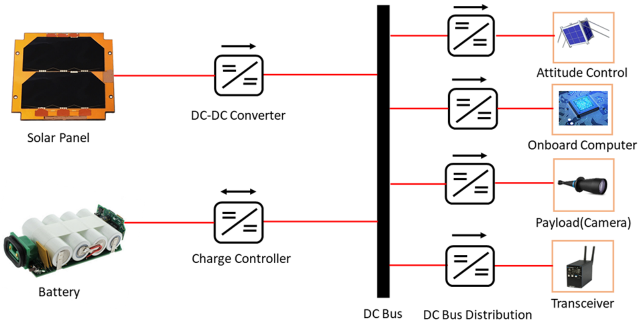

Fig. 1. General Architecture of CubeSat Nanogrid.

This energy balance will help to account for the battery state of charge (SOC), based upon which control algorithm will decide its mode of operation and switching from MPPT mode to current control mode. The overall change in battery SOC in terms of its initial SOC_i and battery ampere-hour (Ah) capacity is given by (2).

$$SOC = SOC_i + \frac{1}{C}\int_0^T \left(I_S - I_L\right) dt \qquad (2)$$

Based upon SOC, a control algorithm is designed for optimal power extraction from PV under varying scenarios of solar power generation and loading requirements. The control algorithm along with the energy management system is discussed in the next section.

3. PROPOSED CONTROL AND ENERGY MANAGEMENT SYSTEM

The power architecture of the CubeSat nanogrid under consideration is shown in Fig. 2. For the considered specifications [16], PV panel voltages at maximum power point V_{MP} are higher than the DC bus or battery voltage V_B, therefore, a DC-DC buck converter is used for the interfacing of Solar panel and battery integration. Based upon the varying profile of solar power generation and load requirements battery state of charge may take different values. For the sunlight conditions, when maximum solar power is available, MPPT control will assume the responsibility for maximum power extraction of the incident solar energy. Thus, if the load demand is not too high in this duration, battery SOC will tend to rise, therefore, a maximum threshold of SOC_{max} is defined to limit the overcharging possibility. Similarly, in the duration of the eclipse, when no solar power is available a mechanism is set to shut down the non-critical loads, therefore, a lower threshold of SOC_{min} is also set to avoid deep discharging of the battery. The information of SOC is communicated via an internal communication link to the controller which is responsible for its operation in either MPPT or current control mode. Both of the modes of operations take place in the power electronics interface circuit shown in Fig. 2 and further discussion is carried out accordingly.

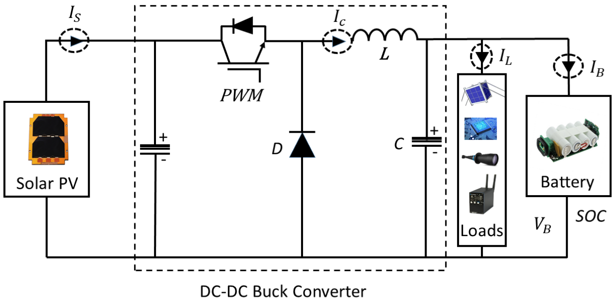

Fig. 2. Power Electronic Interface of CubeSat Nanogrid under consideration.

3.1. Perturb and Observed (P&O) MPPT Algorithm

In order to extract the maximum power from the incident, solar energy MPPT algorithms are used. MPPT is a procedure in which a switch-mode converter is placed in series with the solar array to dynamically regulate the array output impedance to match the loads for impedance matching based maximum power transfer [18]. Therefore, MPPT techniques manipulate either operating current and voltage of the solar array and drive the operating point of the solar array by controlling the operation of the switching converter between the load and solar array. The location of the maximum power point (MPP) depends on the number of parameters like positioning to the Sun, category of the cell used, temperature and total solar insulation coming to the solar cells [18]. As for the solar cell placement in CubeSat, the satellite can track only three power points at any instant of time, therefore three separate MPPT systems are placed within the structure. Since we have lumped our solar cells in the form of a module, therefore, in this analysis we have used a single MPPT tracker. Commonly used MPPT algorithms are perturbed and observe (P&O) method, incremental conductance (IC) method, hill-climbing method. A review of the algorithm MPPT algorithms is discussed in [16]. Other than simplified methods, many advanced and complex methods are also proposed in the literature for global maximum power point tracking (GMPPT) of the PV system under rapidly varying atmospheric conditions and associated irradiance and temperature profiles [19]. Due to its inherent simplicity, least computational complexity, and simplified implementation, P&O algorithm is employed in this work. The detailed flowchart of the P&O method is shown in Fig. 3. In case the operating voltage of the solar array V_S is perturbed in a specified direction and the drawn power P_S of solar module increases, it shows that the operating point has switched in the direction of MPP and, consequently, in the same direction the operating voltage must be perturbed. Otherwise, if the PV array, drawn power decreases, the driving point from MPP has moved away and there is a need for a reversal of the direction of the operating voltage perturbation.

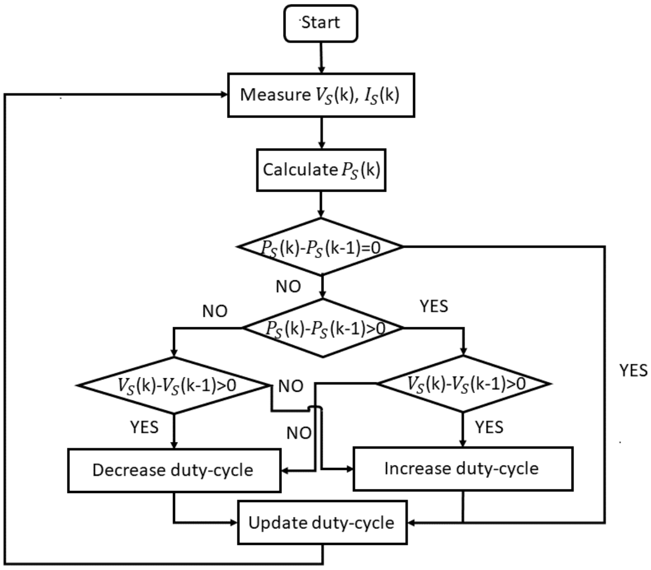

Fig. 3. MPPT flowchart using P&O Algorithm.

3.2. *Switching from MPPT to Current Controlled Mode*

Based upon the loading profile and incident irradiance, the difference between the net influx of input and output power either tends to increase or decrease SOC as dictated by (2). The battery SOC if not constrained may lead to overcharging and subsequent gasification leading towards high rates of battery lifetime degradation. Therefore, upon approaching the maximum threshold of SOCmax, the battery shifts its mode from MPPT mode to the current-controlled mode. The internal communication link that is dedicated to the communication of information regarding SOC, is used for the communication of varying load information. Therefore, as shown in Fig. 4, buck converter shifts its mode to current control mode by generating a duty cycle according to (3).

$$d = k_p \left(I_L - I_c\right) + k_i \int_0^t \left(I_L - I_c\right) dt \tag{3}$$

Where d is the duty cycle of the converter and associated PWM ensures that the current extracted from solar by the converter I_C exactly matches the incident load requirements I_L. Also, k_p and k_i are the proportional and integrational control constant used for the tuning of the PI controller.

It is worth mentioning here that since the battery is already approaching its maximum state, therefore, it will have enough capability to regulate the DC bus voltage and solar is just responsible for powering load through power curtailment exactly equal to load requirements. Since now solar PV is generating power exactly equal to the load requirements, therefore, net energy entering into the battery will be zero and according to (2), the net change in battery SOC will be zero during this operation mode. Therefore, it will not impact the battery life, meanwhile, the control scheme will optimally extract the maximum utilizable power from solar PV.

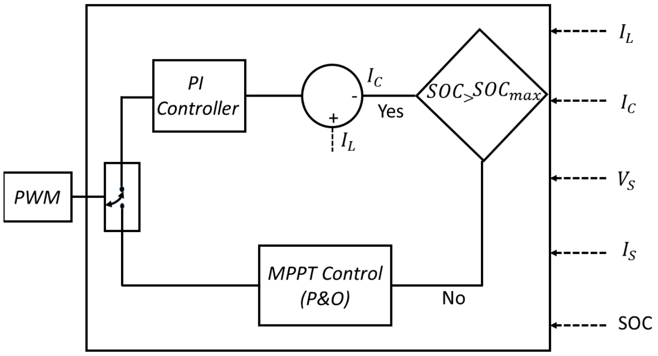

Fig. 4. SOC based Control Mode Switching Scheme.

4. ESTCUBE-1 CASE STUDY, SIMULATION AND RESULTS

For the validation of the proposed control and EMS, the parameters of ESTCube-1 designed for low earth orbit are considered [16]. The varying load profile of various subsystems during the mission is given in [16]. Similarly, incident irradiance values are also taken from [16]. The detailed parameters for the simulated case study are lumped for simplification and are listed in Table 1. The simulation results for various loading and various incident irradiance scenarios is shown in Fig. 4.

Fig 5 (a) corresponds to the incident irradiance in low earth orbit during sunlight and eclipse mode. The satellite remains in sunlight for up to t = 0.4 s, while remains in eclipse from t = 0.4 to 0.5 s. Due to the low air mass, incident irradiance in space is higher than on the surface of the earth, therefore, a 10W$_p$ peak panel produces much higher power in space than on earth.

Table 1. Parameters of Simulated Case Study

Description of Parameter	**Value**
Lumped Power of Solar Module	10W$_p$@1000W/m^2
Maximum Power Voltage V_{MP}	9 V
Maximum Power Current I_{MP}	1.1 A
Battery Capacity C	2200 mAh
Battery Voltage V_B	8V
Full-load power P_L	13.4 W
Limited Functionality Load P_L	6.7 W
SOC_{max}	80%
SOC_{min}	40%
Incident Solar in Irradiance Low Earth Orbit	1300 W/m^2
Control Constants k_p, k_i	0.2, 13
Buck Converter Inductance L	1.3 mH

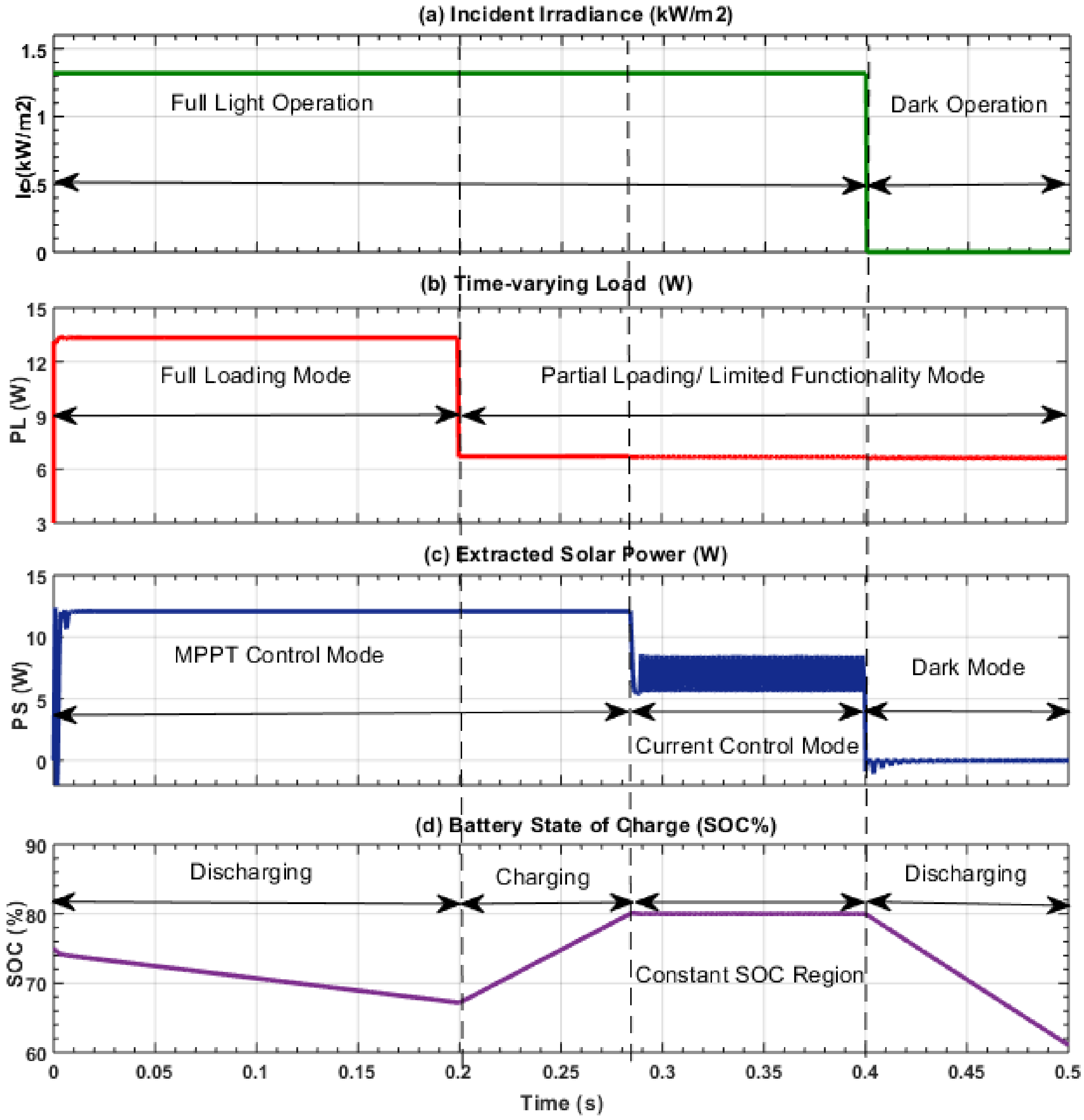

Fig. 5 (a) Incident Irradiance Profile in Low Earth Orbit, (b) Time-Varying loading profile, (c) Solar Power Extraction Profile, and (d) Battery SOC Profile under Varying Load and Solar profiles

Fig. 5 (b) corresponds to the time-varying lumped loading profile of the satellite. From Fig. 5 (b) it can be seen that from t = 0 to 0.2 s, CubeSat is operating in Full-load mode, where all the subsystems are operating, while from t = 0.2 s to 0.5 s it is operating in limited functionality mode, power critical subsystems only. From Fig. 5 (c) shows the extracted solar power by the buck converter. It can be observed that at the start of the simulation that since CubeSat is operating its full load, and high PV irradiance is available, therefore buck converter is operating in MPPT mode extracting the maximum possible power from the incident solar light. Despite extracting the maximum available power, it is not sufficient to fulfill the load demand by the solar power only, therefore, the battery also contributes to the net load power demand, as a result of which its SOC starts decreasing at the start of the simulation as shown in Fig 5 (d). At t= 0.2 s, CubeSat shifts its loading mode from full load operation to limited functionality mode. Since irradiance is available and converter is already operating in MPPT, therefore, the converter will continue to extract the maximum power, part of which will be used for battery charging and remaining is used for load requirements. As shown by Fig. 5 (d), during this condition, battery SOC increases, until it reaches to SOC_{max}. Once battery approaches SOC_{max}, despite the full irradiance availability, solar converter shifts its mode from MPPT to current control mode, thereby limiting its power according to the incident load requirements. It can be observed in Fig. 5 (c) that at t= 0.28 s and onwards up to t= 0.4 s, average power extracted from the solar exactly matches with the load requirements. Therefore, curtailing is achieved using current control. This is also visible in Fig. 5 (d), that during this time interval, when the solar converter is operating in the current control mode, battery SOC does not vary and remains fixed at 80%. Therefore, optimal power curtailment has been achieved. From t = 0.4 s to 0.5 sec, CubeSat enters in the eclipse, resulting in zero irradiance. As a result of which solar power drops to zero and the battery start supplying to the load based upon its energy availability and load requirement. Thus it can be observed from the results that optimal can be extracted from solar PV using the proposed control scheme and energy management system.

5. CONCLUSION

This work presents an adaptive control algorithm for optimal solar power extraction and is highly suitable for CubeSat applications. Energy management through the proposed control scheme allows optimal battery charging as well as enhanced battery life. It is shown through the results that converter has the capability to switch from MPPT mode to the control mode based upon the SOC threshold and once converter enters in the current controlled mode, its SOC remains constant, irrespective of the incident irradiance. The proposed control and energy management system has the capability to curtail PV power extraction in accordance with the incident load requirements to avoid battery overcharging. Future work involves the energy management of the Point of Load (POL) side converters at different voltage levels and their coordination for efficient resource utilization in CubeSat applications.

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BIOGRAPHY

Mohammad Yaqoob received the B.S degree in electrical engineering from Balochistan University of Engineering and Technology Khuzdar (BUETK), Pakistan in 2006 and the M.S degree in telecommunication engineering from Asian Institute of Technology (AIT), Bangkok Thailand in the year 2012. He is currently employed (on study leave) in Balochistan University of Engineering and Technology Khuzdar Pakistan as an assistant professor in Electrical Engineering Department and he has worked on the key administrative position of the Director, Quality Enhancement Cell (QEC) for two years in the same Institution. This time he is a Ph.D. student in the Center for Research on Microgrids (CROM), Department of Energy Technology, Aalborg University, Denmark.

Mashood Nasir received his BS degree in Electrical Engineering from UET Lahore, Pakistan and MS in Electrical Engineering from UMT Lahore, and Ph.D. in Electrical Engineering from Lahore University of Management Sciences, Pakistan in 2009 and 2011, and 2018 respectively. From 2011 to 2012, he served as a lecturer and from 2013-2014 he served as an assistant professor in the Electrical Engineering department at UMT, Lahore. From, May 2017 to Nov 2017 he was a visiting Ph.D. researcher at the Microgrid Laboratory in Aalborg University Denmark. From 2018-2019 he served as an assistant professor at Lahore University of Management Science. Currently, he is a postdoctoral research fellow at Aalborg University Denmark. His research interests mainly include but not limited to power electronics, electrical machines and drives, grid integration of alternate energy resources, electrochemical energy conversion and battery storage systems and AC/DC/Hybrid microgrids.

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Josep M. Guerrero (S'01–M'04–SM'08–FM'15) received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, Spain, in 1997, 2000, and 2003, respectively. Since 2011, he has been a Full Professor in the Department of Energy Technology, Aalborg University, Aalborg, Denmark, where he is responsible for the Microgrid Research Program. Since 2012, he has been a Guest Professor at the Chinese Academy of Science, Beijing, China and the Nanjing University of Aeronautics and Astronautics, Nanjing, China; since 2014, he has been the Chair Professor in Shandong University, Jinan, China; since 2015, he has been a Distinguished Guest Professor in Hunan University, Changsha, China; and since 2016, he has been a visiting Professor Fellow in Aston University, Birmingham, U.K. His research interest is oriented to different microgrid aspects, including power electronics, distributed energy-storage systems, hierarchical and cooperative control, energy management systems, smart metering and the Internet of things for ac/dc microgrid clusters and islanded minigrids; current research interest especially focused on maritime microgrids for electrical ships, vessels, ferries, and seaports. Prof. Guerrero is an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and the IEEE INDUSTRIAL ELECTRONICS MAGAZINE, and an Editor of the IEEE TRANSACTIONS ON SMART GRID and the IEEE TRANSACTIONS ON ENERGY CONVERSION. He was the Chair of the Renewable Energy Systems Technical Committee of the IEEE Industrial Electronics Society. He received the IEEE TRANSACTIONS ON ENERGY CONVERSION Best Paper Award for the period 2014–2015. In 2014 and 2015, he received the Highly Cited Researcher Award by Thomson Reuters, and in 2015, he was elevated as the IEEE Fellow. He has been awarded the Villum Investigator award in 2019 for research on microgrid clusters.

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