Smart Hybrid AC-DC Microgrid Test-bed for Power System Studies & Restructuring Laboratory - Part I

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***Abstract*—Restructuring of traditional regulated and centralized power systems has brought the new concept of microgrids in distribution networks. Microgrids could be attractive options to optimally apply the benefits of distributed generation and provide a secure and resilient power supply paralleled with the main grid. A smart AC-DC hybrid microgrid test-bed is designed and implemented in Power System Studies & Restructuring Laboratory in the Faculty of Engineering of Ferdowsi University of Mashhad to provide a microgrid-based framework to design, test, analyze and validate new operation methods in distribution networks. In this paper, an optimal design of a laboratory scale microgrid is presented. The lighting load of the laboratory is redesigned & simulated to comply with the lighting standards. The smart lighting system and its related communication technologies are also explained in the paper. To design a proper photovoltaic system for the microgrid, a comprehensive simulation based on accurate geographical location, 3D shading models and weather data is performed using System Modeling Advisor (SAM) software.**

Keywords*— hybrid microgrid; test-bed; smart LED lighting; photovoltaic

I. INTRODUCTION

Driven by power system restructuring, increased Distributed Energy Resources (DER) penetration and risks of constructing massive generation and transmission facilities, generating companies are gradually shifting to smaller and decentralized units. Thus, distribution system structure are moving toward microgrid systems. Microgrids could be attractive options to optimally apply the benefits of distributed generation. Moreover, in the cases where providing a secure power supply is of high importance for the consumers, microgrids play a fundamental role. Microgrids have several applications in military bases, remote villages and communities, places requiring high reliability or power quality, important data centers, municipal & governmental applications and high cost electricity-supply regions. Microgrids are formed by distributed generators, variety of customer loads and distributed energy storage devices. They have the advantageous of improving energy efficiency, reducing environmental impacts and enhancing power system reliability. Several definitions have been suggested for the microgrids. The U.S. department of energy defines a microgrid as: ‘‘a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can be connected or disconnected from the grid to be enable to operate in both grid-connected or island mode” [1].

One of the main functions of microgrids is to ensure proper operation during faults and different network disturbances [2, 3]. The main three technical challenges about microgrids are voltage and frequency control, islanding and protection which are comprehensively reviewed in [4].

The existing microgrid test networks in North America, Europe and Asia are:

- Boston Bar – BC Hydro microgrid and Boralex planned islanding – Hydro Quebec (HQ) microgrid both in Canada
- The CERTS test-bed, IIT microgrid and UW microgrid in the United States
- Bronsbergen Holiday Park microgrid in Netherlands
- The Residential microgrid of Am Steinweg in Stutensee in Germany
- CESI RICERCA DER test microgrid in Italy
- Laboratory-scale microgrid system at National Technical University of Athens (NTUA) in Greece
- DeMoTec test microgrid system in Germany
- University of Manchester microgrid/flywheel energy storage laboratory prototype in UK
- Aichi microgrid project Central Japan airport city
- Kyoto eco-energy project (Kyotango project), Hachinohe project, Test network at Akagi of the Central Research Institute of Electric Power Industry (CRIEPI) and Sendai project in Japan
- Microgrid test-bed in Hefei University of Technology (HFUT) and Laboratory scale microgrid in China

- And Test microgrid at the Institution of Engineering and Technology in India

Characteristics of the aforementioned microgrids are summarized in Table 1 and three of them are explained in more details as follows.

A. The AC Boston Bar – BC Hydro microgrid:

The AC Boston Bar – BC Hydro microgrid with the peak load of 3 MW, is interconnected to a 69 kV feeder through 69/25 substation which is comprised of three radial feeders. This microgrid was built to solve the frequent power outages of 12 to 20 hours periods due to permanent outages on the 69 kV line between the substation and the BC Hydro grid. There are two 4.32 MVA run-of-river hydro power generators connected to one feeder and an on-site 55 kW diesel generator for black start capability. The microgrid is not equipped with storage system, but the inertia of the generators is increased to improve the transient response. The voltage of Point of Common Coupling (PCC) is regulated by Automatic Voltage Regulation (AVR) control. Overcurrent protection for grid-connected and island modes is utilized [5], [6].

B. Bronsbergen Holiday Park microgrid

Bronsbergen Holiday Park microgrid consists of 208 holiday homes in the park with 108 roof fitted photovoltaic panels. The peak generation capacity of the photovoltaic panels is 315 kW. The microgrid is connected to a 10 kV medium voltage grid through 400 V/ 10 kV substation with capacity of 400 kVA. The system is equipped with two battery banks connected to PCC. [5], [7].

C. The Residential Microgrid of Am Steinweg in Stutensee

The Residential Microgrid of Am Steinweg in Stutensee is a three-phase low voltage four-wire system, connected to the medium voltage network through a 400 V/ 20 kV substation with a 400 kVA transformer. This microgrid consists of a CHP with available power of 28 kW, photovoltaic with nominal power of 35 kW, a 880 Ah lead acid battery which is connected by a bi-directional 100 kW inverter. 101 apartments are linked to the microgrid. To operate the test system, a power flow and a power quality management system (PoMS) is used. PoMS is a tool to perform grid operation, DG control and demand side management [8], [9].

TABLE I. MICROGRID TEST-BEDS AROUND THE WORLD

Micro-grid test-beds	**Country**	**Photovoltaic**	**Solar thermal**	**Wind**	**Fuel cell**	**CHP**	**Hydro**	**Diesel Steam**	**Motor driven**	**Storage**	**Microgrid Control**
Boston Bar – BC Hydro	Canada	-	-	-	-	-	2	-	-	-	Autonomous
Boralex planned islanding – Hydro Quebec (HQ)	Canada	-	-	-	-	-	-	1	-	-	Autonomous
The CERTS test-bed	USA	-	-	-	-	-	-	3	-	Battery	Autonomous
UW microgrid	USA	1	-	-	-	-	-	1	-	-	Autonomous
Bronsbergen Holiday Park	Netherlands	108	-	-	-	-	-	-	-	Battery	Central
Residential microgrid of Am Steinweg in Stutensee	Germany	several	-	-	-	1	-	-	-	Battery	Agent based
CESI RICERCA DER test microgrid	Italy	8	1	1	-	2	-	1	-	battery, Flywheel	Agent based
Laboratory-scale (NTUA) University	Greece	7	-	1	-	-	-	1	-	Battery	Central
DeMoTec test microgrid system	Germany	1	-	1	-	-	-	1	-	Battery	Central
University of Manchester microgrid/ laboratory prototype	UK	-	-	-	-	-	-	-	1	Flywheel	Central
Aichi microgrid project	Japan	3	-	-	7	-	-	-	-	Battery	Central
Kyoto eco-energy project	Japan	2	-	1	1	1	-	1	-	Battery	Central
Hachinohe project	Japan	5	-	4	-	-	-	3	-	Battery	Central
CRIEPI	Japan	3	-	-	-	-	-	-	-	-	Central
Hefei University of Technology (HFUT) Laboratory scale	China	2	-	2	1	-	1	1	-	Battery, Capacitor	Agent based
Test microgrid at the Institution of Engineering and Technology	India	-	-	-	-	-	-	-	1	-	Central

In order to study problems and limitations of developing microgrids, standard test systems are required as pilots. The smart AC-DC hybrid microgrid of PSRES laboratory of FUM in Mashhad is implemented to provide a test-bed for analyzing microgrid studies in fields of planning, operation, control, protection and power quality control. It provides computational tools and techniques to analyze, design and validate the low voltage distribution network studies through microgrid framework. The objective of this paper is to present and discuss the benchmark PSRES laboratory smart microgrid system developed by the science-based company of SIRCo and the researchers of the laboratory. The main emphasis of the paper is placed on the microgrid design and sizing. Operation and control concept of PSRES Lab. microgrid is presented in another paper as part II of this paper. PSRES Lab. Smart Control Software (PLSCS), which is briefly explained in part III of this paper, will be completely presented in our future papers.

II. MICROGRID DESIGN

A. *System Description*

Providing a microgrid structure in the PSRES Lab. seemed essential due to some reasons including, energy demand of emergency lighting, need for comprehensive studies and researches in the field of renewable energy resources, implementation and analysis of noble ideas about microgrid energy management and improvement of necessary power electronic devices for microgrids.

The smart PSRES Lab. microgrid has been designed according to three steps:

- Load estimation considering coincidence factor
- Collecting primary information
- Design of the microgrid

Step 1: Load estimation considering coincidence factor

Among the various methods of electric load estimation, the end use method is utilized broadly. Thus, to estimate the PSRES Lab. load, this method is applied considering coincidence factor. Daily energy consumption of electrical loads in PSRES Lab. is calculated according to the actual usage of the laboratory members as shown in Fig.1. In addition, annual energy consumption of the PSRES Lab. is calculated based on estimation of demand in past years (Fig.2) [10]. Daily load profile and monthly load profile are shown in Fig.3 and Fig.4 respectively based on HOMER simulation results. Peak load of the Lab. is about 6 kW. Coincidence factor for lighting load is considered to be 70 percent. For computers consumption, the coincidence factor is considered to be 60 percent for summer time and 80 percent for the rest of the year. Coincidence factor for battery chargers is assumed to be 80 percent.

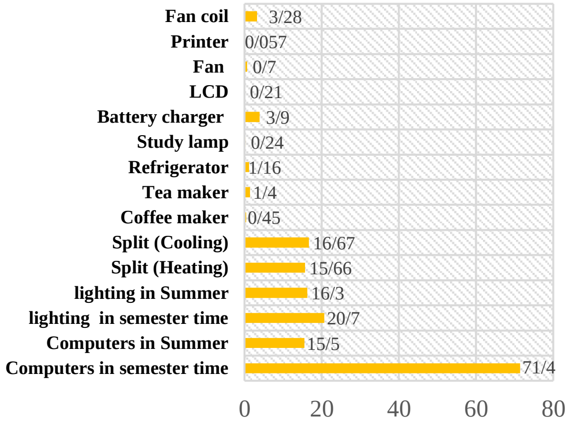

Fig.1: Average daily energy consumption of electrical loads in PSRES Lab. (kWh)

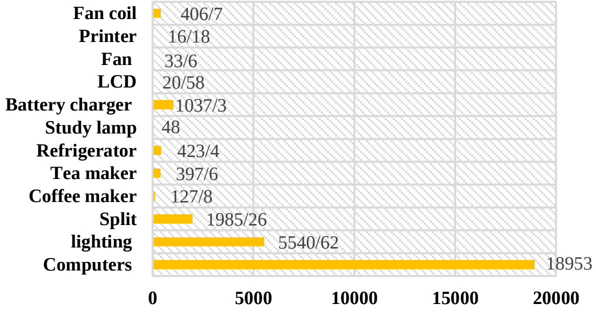

Fig.2: Annual energy consumption of electrical loads in PSRES Lab. (kWh)

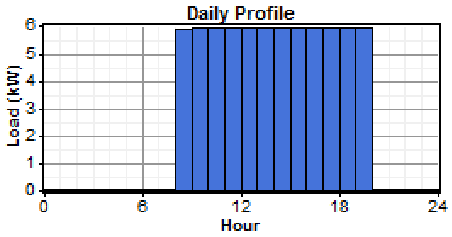

Fig.3: Daily load profile

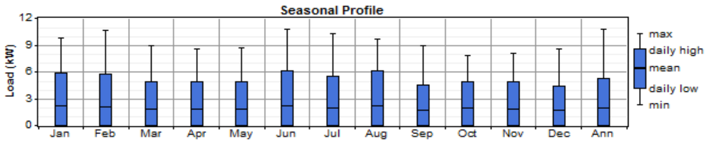

Fig.4: Monthly load profile loads in PSRES Lab. (kWh)

Step 2: Collecting primary information

After investigating different possible structures of microgrids, an AC-DC hybrid microgrid is selected to be implemented in the PSRES Lab. In order to reduce switching losses of power electronic devices in this structure, AC demands and DC demands are connected to AC bus and DC bus, respectively.

According to the requirements of the PSRES Lab., three different types of structures for the AC-DC microgrid have been studied. The structures are illustrated in Figs.5-7. Voltage of the DC bus in the types 1 and 2 is selected to be 48V, which is a suitable voltage level for supplying smart lighting and charging four 12V - 100Ah batteries. The control of battery charging and supplying the lighting demand with photovoltaic panels and electricity grid are handled with solar charge controller and controllable Switched-Mode Power Supply (SMPS), respectively.

The main difference between type 1 and type 2 is about inverting DC to AC for supplying AC demands, in the island mode. In type 1, this procedure is done by an inverter while in type 2, solar charge controller has this responsibility.

In type 3 of microgrid structure, a special device has been utilized which contains all the necessary power electronic devices. This particular device has various AC and DC ports including photovoltaic panels' ports and grid port. Moreover, it provides not only DC output for supplying DC loads and battery charging, but also it can supply AC loads as well. This type of microgrid structure was omitted from the list of possible plans, due to the difficulties of obtaining the abovementioned hybrid charge controller.

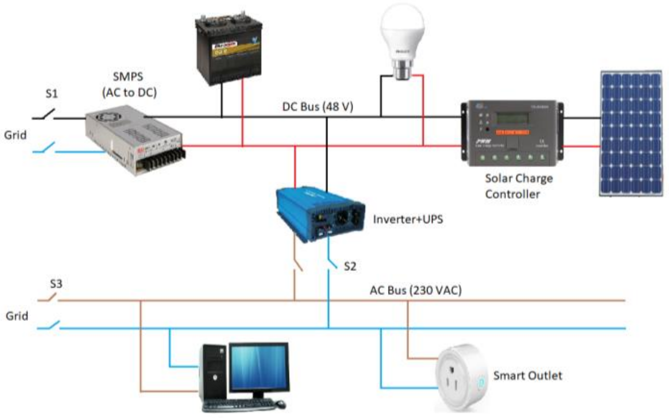

Fig.5: Microgrid structure, type1

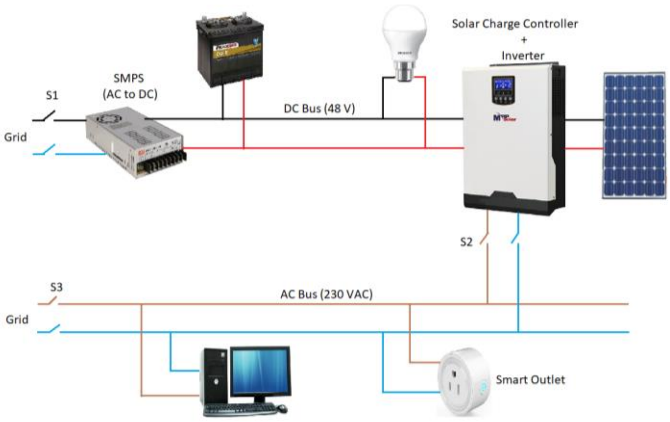

Fig.6: Microgrid structure, type2

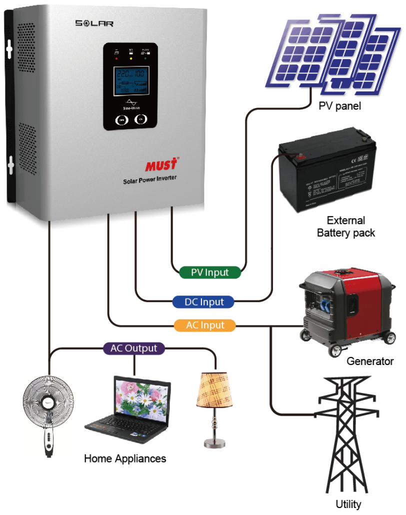

Fig.7: Microgrid structure, type3

Step3: Design of the microgrid

Between type 1 and type 2 of microgrid structures, the type 1 has been chosen as the final plan. This is mainly because of the higher reliability, more safety and protection, its extensibility and simpler troubleshooting and maintenance.

B. *Technical Specification of Equipment*

The necessary equipment, specified in previous section, are provided according to technical requirements of the microgrid and cost management. Technical specification of equipment is expressed in table II. It should be noted that the optimal sizing of all the equipment is based on the total electricity demand of the PSRES Lab.

TABLE II. TECHNICAL SPECIFICATION OF EQUIPMENT

Equipment	Specifications
PWM solar charge controller	• 20A • 12/24/36/48V • RS485/RJ45 interface
AC to DC Converter	• 1600w • 27.5A • 93.5% efficiency
Solar panel	• 2*250w • 37.5V open circuit voltage • 8.8A short circuit current • 30V MPP voltage, 8.33A MPP current • 1640*992*35 mm module dimension
Wind turbine	• 1*200W
Battery	• 100Ah • 12V
Solar tracker	• Single axis • 60 degree

III. MICROGRID SMART CONTROL OF LIGHTING

A. Lighting Design & Simulation

In this section, a general review of designed LED panels for lighting of the laboratory and acquired illumination by means of these panels are presented. All the LED panels are designed and built by SIRCo. Each panel consists of 6 LED branches consuming 26 W with the total luminous flux of 3200 lumens.

In order to analyze the lighting system of the Lab. in the presence of designed LED panels, the DIALux [11] software was utilized. For this purpose, a 3D model of the Lab. was constructed in DIALux medium and illumination of different parts in the Lab. is evaluated. The illuminance isolines of the laboratory which is calculated in DIALux software is shown in Fig.7. Based on the illumination standard by the national illumination committee of Iran [12] and [13], the suggested amount for the Lab. is 500 lux, which is satisfied by using designed LED panels.

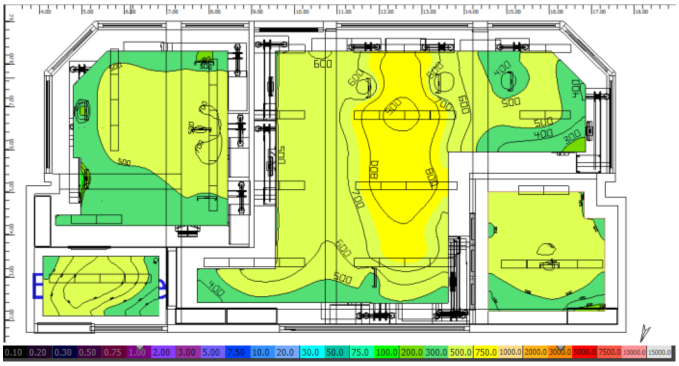

Fig.7: Illuminance isolines of the laboratory

Table III specifies some remarkable indices, indicating the illuminance of the Lab., obtained from the DIALux software. These indices prove that the illumination of the laboratory satisfies the national and international standards.

TABLE III. OUTPUT OF THE DIALUX SOFTWARE

Test Positions	Avg.(Lux)	Min/Avg.	Min/Max
1	672	0.63	0.52
2	588	0.42	0.27
3	743	0.38	0.26
4	667	0.4	0.31

B. Smart lighting system

For the purpose of control and management of the smart PSRES Lab. microgrid, central control architecture is adopted. A server computer with PSRES Lab. Smart Control Software (PLSCS) acts as central control unit. This software is based on python framework and is developed by the members of SIRCo and the PSRES researchers. Microgrid administrators can access to the software over the Internet and control the microgrid state.

For smart control of lighting, various sensors including presence, distance and light sensors are installed in the Lab.. All of the sensor boards are designed and built by the members of SIRCo. The sensors are connected to the central control unit using wireless network.

The first step in wireless network design is choosing suitable communication technology. There are various types of wireless communication technologies that are different in range, energy consumption, security and compatibility. Three well-known wireless technologies are compared in table IV [14].

According to specifications of the smart PSRES Lab. microgrid, ZigBee technology is selected for wireless networking. ZigBee is an IEEE 802.15.4-based specification with low power consumption and low data transfer rate which is suitable for smart control purposes. ZigBee networks can have one of the following four topologies: star, tree, cluster tree and mesh. In PSRES Lab. microgrid, mesh topology is chosen. This topology has some advantages including self-healing ability, ease of removing or adding new devices, elimination of dead zones and increasing range [15].

TABLE IV. COMPARISON OF WIRELESS TECHNOLOGIES

	ZigBee	WiFi	LoRaWAN
Frequency Band	915MHz / 2.4GHz	2.4GHz	Varies, Sub-GHz
Typical Range	100m/Mesh	50m	2-5 urban; 15 suburban; 45km rural
Data Transfer Rate	250kbps	600mbps max	0.3-50 kbps adaptive
Power Consumption	Low	High	Low

In order to control lighting system, various scenarios can be defined in PLSCS. Based on received data from the sensors and user preferences, PLSCS determines the suitable light intensity and sends proper instructions to microcontrollers which are installed near each LED driver. The microcontrollers produce appropriate Pulse Width Modulation (PWM) waves which control the current of LED drivers to dim the LEDs.

IV. SOLAR PANEL SIMULATION

The generated energy of photovoltaic panels and the shading and soiling losses have been simulated by System Advisor Model (SAM) software developed by NREL [16].

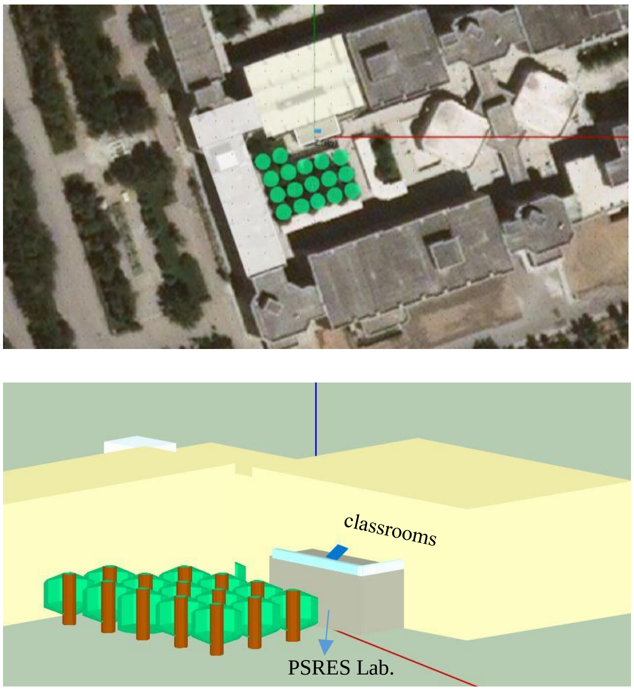

Fig.8. Aerial image and 3D scene of PSRES Lab.

To assess the effect of tilt angle and sun tracker on annual absorbed energy of panel, some scenarios are introduced. The simulation consist of the amount of Plane-of-Array (POA), annual absorbed DC energy and shading losses, which are presented in Table V. For each scenario, soiling losses are about 5 percent.

Net DC energy could be calculated using Equation (1).

$$\begin{aligned} \mathit{Net\ DC\ energy} &= \mathit{POA} * \mathit{Module\ efficeincy} \\ &* (100 - \mathit{shading\ losses})/_{100} \\ &* (100 - \mathit{soiling\ losses})/_{100} \end{aligned} \quad (1)$$

It should be noted that azimuth angle at fixed structure scenario is 180^{0} which means the module is faced to the south. As shown in table VI, using a single axis sun tracker with 60^{0}-rotation limit and tilt angle of 36^{0}, could be the best choice for microgrid power supply. Although using a dual axis sun tracker causes more production, but the amount of additional absorbed energy is negligible. 3D shade calculator of SAM software is used to simulate this scenario's shading conditions. Simulated monthly produced energy is shown in Fig. 10. The simulated capacity factor assumed ideal solar charge controller is 24.9%. Simulated annual absorbed energy is approximated to be 2182 kWh/kW.

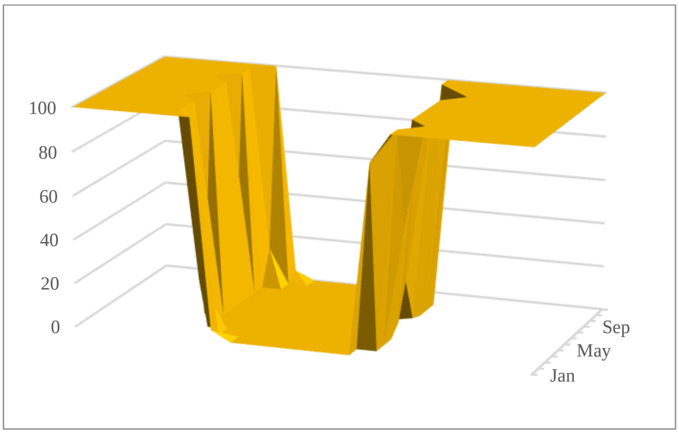

Fig.9. Simulated Montly shading coefficient

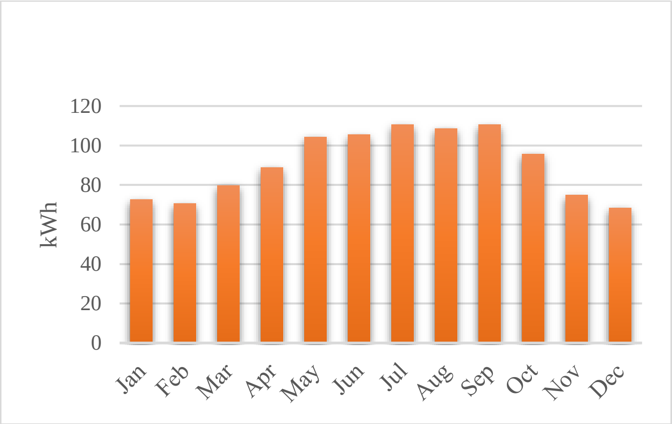

Fig.10. Simulated monthly produced energy

TABLE V. SCENARIOS' SIMULATED RESULTS

Tilt angle (^{0})	Sun tracker status	POA (kWh)	Net DC Energy (kWh)	Shading losses (%)
36	Fixed structure	6238	855	6.108
40	Fixed structure	6200	855	5.499
40	$\pm 45^{0}$, single axis	7818	1048	8.113
40	$\pm 60^{0}$, single axis	7953	1060	8.694
40	$\pm 85^{0}$, single axis	8007	1062	9.127
36	$\pm 45^{0}$, single axis	7851	1051	8.269
36	$\pm 60^{0}$, single axis	7981	1063	8.754
36	$\pm 85^{0}$, single axis	8029	1065	9.103
36	Dual axis	8294	1099	9.190
40	Dual axis	8294	1098	9.256

V. CONCLUSION & DISCUSSION

In this paper design of the smart hybrid AC-DC microgrid of PSRES Lab. has been presented through three steps of load estimation, collecting primary information and design of the system. The optimal design of the laboratory scale microgrid for the PSRES Lab. was chosen among three cases. The lighting load of the laboratory, which consists LED panels, were redesigned & simulated in DIALux software to comply with the lighting standards. The smart controlling of LED lighting is introduced and its related communication technologies were compared with each other in the paper. The proper photovoltaic system was designed through a comprehensive simulation by SAM software considering sun tracker status, shading losses, net DC energy, tilt angle of the panel and POA.

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