DESIGN OF A ONE-WAY COMMUNICATION BASED CONTROL SCHEME FOR POWER MANAGEMENT UNIT IN SCALABLE DC MICROGRID ARCHITECTURE

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MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

by

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The thesis titled "**DESIGN OF A ONE-WAY COMMUNICATION BASED CONTROL SCHEME FOR POWER MANAGEMENT UNIT IN SCALABLE DC MICROGRID ARCHITECTURE**" submitted by Abu Shahir Md. Khalid Hasan, Roll No.: 0416062129 P, Session: April 2016, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING on August 24, 2019.

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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Dedication

to my Family

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Abstract

Renewable energy has gained much interest in recent years to keep the environment safe from ongoing climate change and become less dependent on fossil fuels. DC microgrids adapts nicely to distributed control of renewable energy sources to supply electricity in the remote regions. They ensure efficacious instantaneous power sharing among different domestic Power Management Units (PMUs) along with maintaining stability of the grid voltage. Here design metrics and performance evaluation of a scalable DC microgrid are documented where a source converter initially complies with the efficient power sharing phenomenon among a set of two home PMUs. The source converter is connected with a Photovoltaic panel of 300 W and uses Perturb and Observation (PO) method for executing Maximum Power Point Tracking (MPPT). A boost average DC-DC converter topology is used to enhance the voltage level of the source converter before transmission. The load converter consists of parallel PMUs. Each PMU is constructed with high switching frequency based Full Bridge (FB) converter to charge an integrated Energy Storage System (ESS). The overall system is modeled and simulated on MATLAB/Simulink platform with ESSs in the form of Lead Acid batteries connected to the load side of the FB converter circuits and these batteries yield to support marginalized power utilities. The behavior of the system is tested in different solar insolation levels along with several battery charging levels of 12 V and 36 V to assess the power efficiency. In each testbed the efficiency is found to be more than 93% which affirm the reliability of the framework and a look-up table is generated comprising the grid and load quantities for effective control of power transmission. Next the full bridge (FB) converter is used as the fanout node to lower the source-end voltage and to generate a dc bus of 48 V. Buck converter topology is used to design the PMUs and each PMU is controlled in a way to generate an output voltage suitable for a 12 V battery charging application. A one-way communication control based interface is designed to maintain the change in the solar irradiation level so that the more important units receive more power in a crisis situation. To make the system more sensible in case of long duration drop in solar irradiance level, a time based control scheme has been proposed which ensures that the turn off time is distributed evenly among the PMUs. The system works successfully for different irradiation pattern. The one-way communication based approach represent less circuit complexity and a cost effective control scheme for DC microgrid in the perspective of underprivileged people of Bangladesh.

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Chapter 1

Introduction

Fossil fuels are nonrenewable, that is, they draw on finite resources that will eventually dwindle, becoming too expensive or too environmentally damaging to retrieve. In contrast, renewable energy resources—are constantly replenished and will never run out. Renewable energy technologies provide an excellent opportunity for mitigation of greenhouse gas emission and reducing global warming through substituting conventional energy sources. In this chapter different from of renewable energy and their growing potential in Bangladesh is described. Motivation for using DC microgird as a renewable energy technology is also narrated here.

1.1 Present scenario of Microgrid development in Bangladesh

Bangladesh possesses a significant potential for electricity generation from renewable energy resources such as solar PV, wind, hydro and biomass. Solar PV has been an emerging technology for the last decade in Bangladesh, mainly in the form of solar home systems (SHS) in rural areas, which can only meet the basic demands of individual households. There are a few off-grid minigrid hybrid systems developed with solar PV that are in operation now [1-3].

Bangladesh's government has taken many initiatives to utilize renewable energy sources, particularly solar PV, to address the electricity crisis of remote areas [4]. The solar home system (SHS) was initiated in 2003 to provide electricity to the remote communities of Bangladesh and gained worldwide recognition. Up to May 2017, approximately 4.12 million SHSs have been installed throughout the country under this program, which is cost-effective and environment-friendly [5]. These small electricity access systems consist of a 20–100 Wp solar panel, a lead acid battery, a charge controller and basic loads currently providing reliable electricity to more than 16 million people in off-grid remote areas. However, major limitations of this electrification option include: affordability of the poorest demographic segment [6]; limitations to utilizing the energy for productive purposes [7] as the systems often suffer from excess capacity because they are generally designed over-sized to ensure high reliability; and the systems are not flexible regarding usage patterns and payment methods [8]. Moreover, a field-based investigation identified several shortcomings, mostly during the implementation stage, such as poor-quality components, poor installation, and absence of quality control mechanisms [2].

Islanded microgrids with distributed energy resources, also referred to as minigrids in literature, have been increasingly attractive in recent years in the rural areas of Bangladesh as they can provide reliable power to the community. A detailed study of the hybrid minigrid project in Bangladesh is discussed in [2, 3]. Chowdhury et al. [2] indicate that the minigrid can be a useful tool to achieve the Sustainable Energy Access for All (SEforALL) [9] goals as the proposed hybrid minigrid system is technically and economically viable for Bangladesh. In addition to techno-economic analysis, Bhattacharyya [3] presented a business case analysis of a minigrid-based electrification system for Bangladesh. Model results show that low-energy consumers will pay almost one-half of the cost of owning an SHS for a comparable level of energy use. However, the proposed system is not economically viable if the consumer uses a high volume of energy, which requires significant upfront costs. A large-scale minigrid also introduces energy losses during the off-peak period. Therefore, the author suggested a small-scale mini-grid based electricity supply that provides a basic level of electricity to consumers.

There has been no work in one-way communication based approach microgrids in Bangladesh that can increase the effectiveness of power sharing in microgird. So developing control scheme of microgrid can certainly make the microgid system more reliable in our country.

1.2 Motivations for Rural Electrification Energy

Energy poverty is predominantly a rural issue. The cost of PV ($/W) has fallen substantially in the last 10 years (shown in Fig. 1.1). In addition, the compact and modular nature of solar-panels makes them ideal candidates for electricity-generation in remote, rural regions with limited transportation infrastructure. Based on the above factors, there is a basis for hypothesizing that solar PV can prove to be a cheap and sustainable source of generating electricity in areas with low rates of electricity-access.

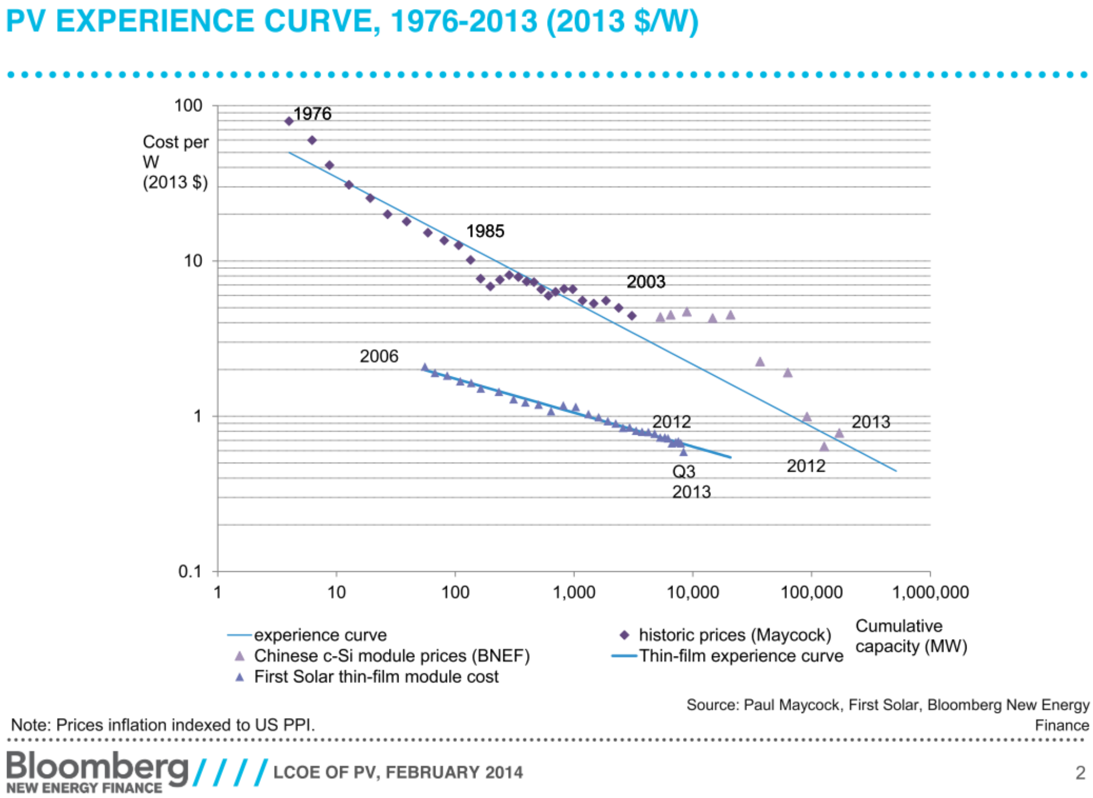

Fig. 1.1 Experience curve of solar PV modules. As the amount of total installed solar PV has grown, the prices of PV modules ($/W) has fallen substantially [10].

1.3 Motivation for One-way Communication based Control Scheme

According to International Energy Agency (IEA) about 1.3 billion people will lack the electricity access even in 2030 [11]. Decentralized electricity generation can help to increase energy access in the remote regions because extension of the grid demands extravagant cost [12]. The AC microgrid has the benefit of using the existing frequency, voltage standards and methods of protection [13-14]. But, in AC microgrid, inverters experience grid-wide brownouts when correlated peaks are observed on the load [15]. The conversion losses are also higher in AC microgrids compared to its DC counterpart [10, 16-17]. Moreover, with the development of power electronics, DC microgrid has a number of new applications in avionics, automotive, marine and manufacturing industries for power distribution [18-23]. Recently, a scalable DC microgrid structure [16-17] is proposed for emerging regions with remote communication-based control where Phase Shifted Full

Bridge (PSFB) [24-25] converter is used to operate in the high voltage side and second stage buck converter is used for smart load sharing. A two-way communication-based control scheme of DC microgrid structure is used there for power management. But such systems need complex circuitry and reliable communication connection for smooth operation. A one-way system should simplify the operation of the system and reduce the cost.

1.4 Objectives of the Thesis

The objectives of this thesis are:

(i) To design and simulate a Phase Shifted Full Bridge (PSFB) Converter based Scalable DC Microgrid architecture with boost converter and MPPT algorithm
(ii) Analyze the performance of the designed system in different loading conditions
(iii)To develop a one-way communication-based control interface for the Scalable DC Microgrid depending on Solar Irradiance level
(iv) To check the performance of system in different temperature level
(v) To implement a time slot based algorithm to improve the performance for tackling long variation in irradiance

1.5 Thesis Overview

This thesis is divided into four chapters.

Chapter 1 provides general introduction followed by necessary background, motivation literature review and the objectives of the work.

Chapter 2 presents detailed mathematical analysis of Full Bridge Converter. The Fanout node and Power Management Units are modeled and their performance was analyzed for different voltage levels at different power ratings and at different frequencies. A control interface is introduced to maintain uniform power sharing in case of variation in irradiance. A timeslot based algorithm is implemented to improve the performance for tackling long variation in irradiance.

The results obtained from the derived model are discussed in chapter 3. Stability of the system is verified checking the efficiency for different voltage level and different frequencies. Furthermore, effect of change in irradiance is shown on the system performance with a control interface in different temperatures and the result of 2 irradiation pattern in the timeslot based control algorithm is presented.

Chapter 4 contains the concluding remarks along with suggestions for future work on the topic.

Chapter 2

Theoretical Framework

The DC microgrid is combination of the PV Array, the source converter and the load converter. The source converter consists of the MPPT control unit and the boost converter. The load converter at first consist the full bridge converter working as the PMU. Then two stage conversion is introduced where full bridge converter is used as the Fanout Node and buck converter is used as the PMU.

2.1 Different forms of Renewable Energy

Most renewable energy comes either directly or indirectly from the sun. Sunlight, or solar energy, can be used directly for heating and lighting homes and other buildings, for generating electricity, and for hot water heating, solar cooling, and a variety of commercial and industrial uses. The sun's heat also drives the winds, whose energy is captured with wind turbines. The Earth's rotation also contributes to the winds, particularly through the Coriolis effect. Along with the rain and snow, sunlight causes plants to grow. The organic matter that makes up those plants is known as biomass. Biomass can be used to produce electricity, transportation fuels, or chemicals. The use of biomass for any of these purposes is called biomass energy. Not all renewable energy resources come from the sun. Geothermal energy taps the Earth's internal heat for a variety of uses, including electric power production and the heating and cooling of buildings. Hydrogen can be found in many organic compounds, as well as water. It's the most abundant element on the Earth. Because energy is always needed to produce hydrogen, it is not an energy source, but a way to store and transport energy, so it is referred to as an energy carrier. The ocean can produce thermal energy from the sun's heat and mechanical energy from the tides and waves. Flowing water creates energy that can be captured and turned into electricity. This is called hydroelectric power or hydropower [26]. Different forms of Renewable Energy is shown in Fig. 2.1

Fig. 2.1 Different forms of Renewable Energy.

2.2 Renewable energy in Bangladesh Perspective

Renewable energy sources are defined as those that are abundant in nature and derived from natural process with no depletion in the course of utilization. Bangladesh is blessed with renewable energy sources such as biomass, wind, solar and small scale hydropower energy [27]. Among the renewables, solar and biomass found promising and effective in the context of Bangladesh [28]. Due to flat terrain and low water head, small scale hydropower found little interest; however, potential of small hydropower energy source is found 500 MW [29]. Utilization of wind energy is limited due to insufficient ground data [30]. Bangladesh is still at nascent stage to utilize renewable energy at commercial scale [27]. However, according to Bangladesh Policy of Renewable Energy (BPRE) 2008, target dissimilation of renewable energy has set to 10% by 2020 [31,32]. Available technology and installed capacity of different renewable energy sources are summarized in Fig 2.2.

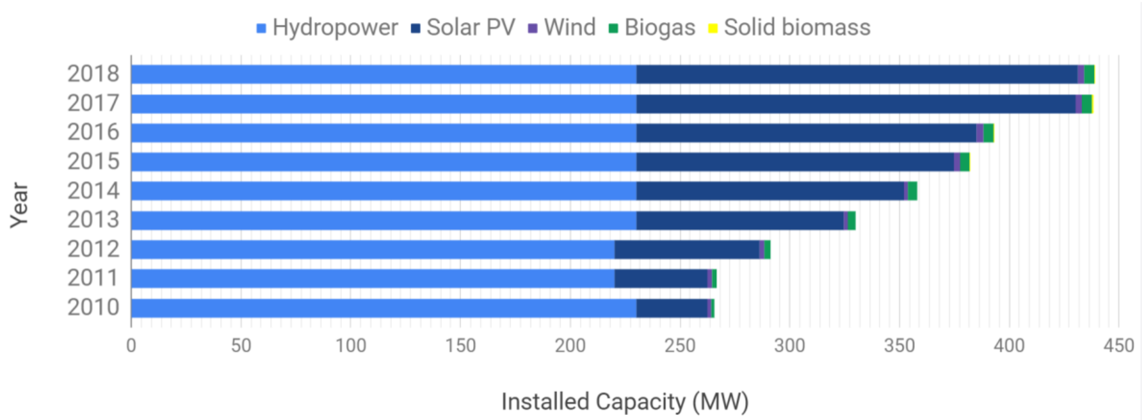

Fig 2.2 Available technology and installed capacity of different renewable energy sources in Bangladesh [33].

2.2.1 Biomass energy

Biomass is extensively used as alternative energy sources in developing countries for the purpose of cooking, heating and other necessary household activities. Generally, biomass refers to rice husk, crop residue, jute stick, wood, animal waste, municipal waste etc. It can contribute to the overall environment quality by reducing emission, and as a promising source of electricity generation. Global biomass energy share will be 50% by 2050, in terms of consumption [1]. Like other developing countries in Asian region, biomass accounts for 48% of the total energy consumption in Bangladesh [34]. In Bangladesh, traditional biomass as energy supply source such agricultural residues, wood wastes and animal dung, represents 46%, 34% and 20%, respectively [35–37]. From environmental and economic sustainability view point, biomass energy is an effective energy source for rural population of the country. Bangladesh is endowed with rich biomass energy with a potential electricity generation capacity of 160.93 TWh from agricultural crop residues, followed by 121.768 TWh from recoverable waste, and 29.91 TWh from fuel wood, saw dust and tree residues [38]. Infrastructure Development Company Limited (IDCOL) has been implementing biogas program in Bangladesh since 2006 with support from the World Bank, KfW Development Bank and SNV Netherlands Development Organization. Biogas plants not only provide gas for cooking purpose but also produce organic fertilizer for the crops and fish pond. The program helps reduce the use of biomass fuel for cooking [39].

2.2.1.1 Biogas

Biogas is a very promising renewable energy resource derived from various residues, mainly from animal and municipal wastes. It can be used for cooking and power generation purposes [40]. Technology dissemination in this particular renewable energy source is very poor all over the country [27,35-36]. Till April 2019, IDCOL has financed construction of over 50,500 biogas plants all over the country [39]. IDCOL also financed a 250 kW biomass based power plant at Kapasia, Gazipur, in which local agricultural residues such as rice husk is used [40]. Municipal solid waste could also be an important source of biogas production [36], which is found very limited application. Fig. 2.3 shows a simplified model of biogas dissemination in rural Bangladesh. However, previous research conducted by the authors in [27] found that as of July 2009, 32% of the total installed biogas plants are not working due to lack of appropriate maintenance and technical knowledge. Constant monitoring and evaluation process should be carried out in the projects sites for project's future sustainability.

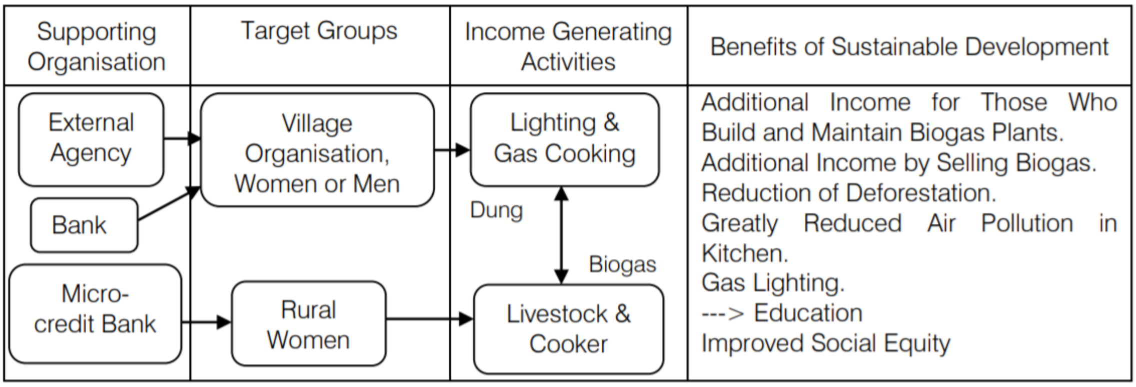

Fig 2.3 Simplified system using biogas [40].

2.2.1.2 Bio-fuel

Biomass utilization is categorized by bio-product, bio-energy and bio-power [41]. So far, Bangladesh is in early stage developing bio-fuel from biomass energy. Biofuel is produced from transesterification of oil derived from various energy crops [42]. Both developed and developing countries are putting effort to commercialize biofuels at large scale. For instance, government of Malaysia, introduced fuel diversification policy where it was emphasized on use of biodiesel as biofuel both in transportation and industrial operations [43]. In the end of 2009, Malaysian biodiesel blend B5 was introduced in the market, to reduce the dependency on imported diesel, and minimizing environmental pollution. B5 is the diesel blend that contains 5% palm oil derived methyl ester and 95% conventional diesel [44]. It is expected, when biodiesel is available all over the country; B5 biodiesel blend will replace 0.5 MT of conventional diesel that will save Malaysian Ringgit (RM) 1 billion, each month [45]. Worldwide, petroleum and other liquid fuels326 are the dominant source of transportation energy, although their share of total transportation energy declines, from 96% in 2012 to 88% in 2040. World transportation sector liquid fuels consumption grows by 36 quadrillion Btu in the Reference case projection, with diesel (including biodiesel) showing the largest gain (13 quadrillion Btu), jet fuel consumption increasing by 10 quadrillion Btu, and motor gasoline (including ethanol blends) increasing by 9 quadrillion Btu (Fig. 2.4) [46].

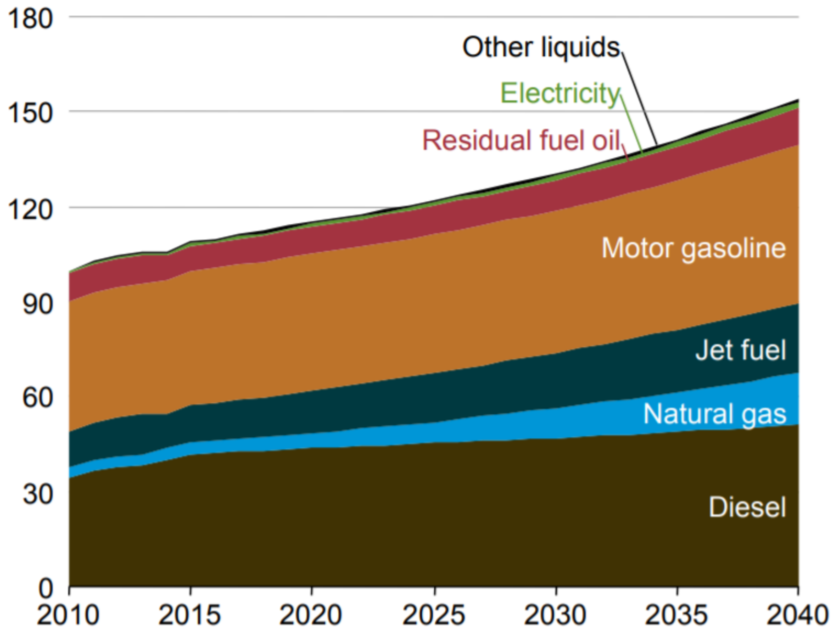

Fig. 2.4 World transportation sector delivered energy consumption by energy source, 2010–40 (quadrillion Btu) [21].

Consumption of this large amount of fossil fuel will account for escalating GHG emission in future. Using biofuels as an alternative in the conventional fuel mix will reduce cost of transportation as well as CO_2 emission. In Bangladesh, there is currently, no energy crops being produced for biofuels at commercial scale; however, on experimental basis, NITOL Motors, Bangladesh (the sole distributor of TATA Motors, India) has started working with two Singaporean firms to produce bio-fuel from ethanol molasses [35]. At initial stage the project will manufacture 12,000 l of bio-fuel, in which feedstock from sugar mills at the northern part of Bangladesh will be utilized [35]. The bio-fuel will be used as gasohol in the transportation vehicle, and the price will be reduced by 20–30% compared to other transport fuel [47]. Bangladesh can also utilize Jatropha curcas as energy crop which is a non-edible plant containing 50–60% vegetable oil. It is comparatively cheap feedstock for biodiesel production, generally grows on degraded soils with less fertility and moisture [48]. J. curcas showed promising qualities as biodiesel in the climatic condition of Bangladesh. From a test operation, it was found that Jatropha showed relatively less emission of CO2 around 1.33% where conventional diesel showed 9% in a diesel engine tested setup [49]. As a developing country, Bangladesh imports large amount of petroleum products with high price from international market. On the other hand, if Jatropha could be used instead of conventional diesel in commercial basis then, Bangladesh could save millions of foreign exchanges. Environmental pollution from transportation sector would also be reduced utilizing such bio-fuel. Public policy regarding fuel regulation and necessary infrastructural should be developed for large scale Jatropha based biodiesel production [50].

2.2.2 Solar energy

All over the world, solar energy is now considered as one of most promising renewable energy source. It has the highest potential to gain energy compared to other renewables. Approximate annual solar radiation on the earth surface is about 3,400,000 exajoule (EJ). Theoretically, available solar energy insolation could generate 1700 TW of electric power, and it is estimated that 1% of this energy can resolve world's present power demand [51]. It is also estimated that solar energy could deliver 450 EJ energy, equivalent to 7500 times higher of the world's energy consumption if the full potential is utilized [52]. Generally, solar energy is being utilized in lighting, heating, and most importantly; in power generation. Technology that is widely used to harness solar energy potential is commonly known as photovoltaic (PV). The construction of solar PV consists of array of solar cells that convert solar light energy to electricity. In the ET scenario, global solar power in 2035 is more than 150% higher than in the base case of the 2015 Energy Outlook. This reflects solar costs falling faster than anticipated, with solar energy now projected to be widely competitive by the mid-2020s – 10 years earlier than previously expected [53]. Both developed and developing countries identified the potential utilization of solar energy through solar PV. Global installed capacity of solar PV increased from 453 MW to 480.357 gigawatt (GW) in between year 1996 and 2018 [33,53]. However, most of the technological development in solar energy sector placed in the developed countries. For instance, in 1996, Germany had solar PV installed capacity of 11 MW which reached 45,930 MW in 2018. Table 2.1 shows solar PV installed capacity in selected Asian economies. Among them India and China are investing aggressively in solar PV sector [52]. Geographical location of Bangladesh is considered to be an ideal place for solar energy utilization [30]. Annual solar radiation available is over 1900 kWh/m2 [30]. Average solar irradiations varies from 4 to 6.5 kWh/m^2 [28]. However, significant variation in data of solar energy is evident, as there is no ground data currently available. Theoretically, Bangladesh receives approximately 69,751 TWh/yr equivalent of solar energy which is 1200 times higher than the electricity generated according to BPDB Annual Report 2016-17 [1, 53]. Average monthly solar irradiation in six divisional districts is presented in Fig. 2.5 [31]. It is found that 94% of the land area in Bangladesh have such radiation which is sufficient for appropriate utilization based on available technology [1]. Maximum radiation begins from March to April, and minimum – December to January [32]. The highest solar radiation is found at Rajshahi district showing an immense potential of solar energy utilization [54].

Table 2.1 Solar PV installed capacity in selected Asian economies (in MW) [33]

Country	Installed Capacity (MW)					
	2013	2014	2015	2016	2017	2018
China	17,748	28,388	43,588	77,788	130,802	175,018
Japan	13,599	23,339	34,150	42,040	49,040	55,500
India	1,283	3,290	5,168	9,418	17,644	26,869
Pakistan	101	165	230	410	742	1568
Malaysia	97.1	165.8	229.1	278.8	317.4	437
Bangladesh	94.6	121.9	144.8	155.2	200.2	201.1
Sri Lanka	12.5	22.4	36.8	79.5	120.6	159.1
Myanmar	4.21	7.68	25.70	54.91	54.91	54.91
Nepal	10.82	11.54	13.38	13.55	53.27	53.27

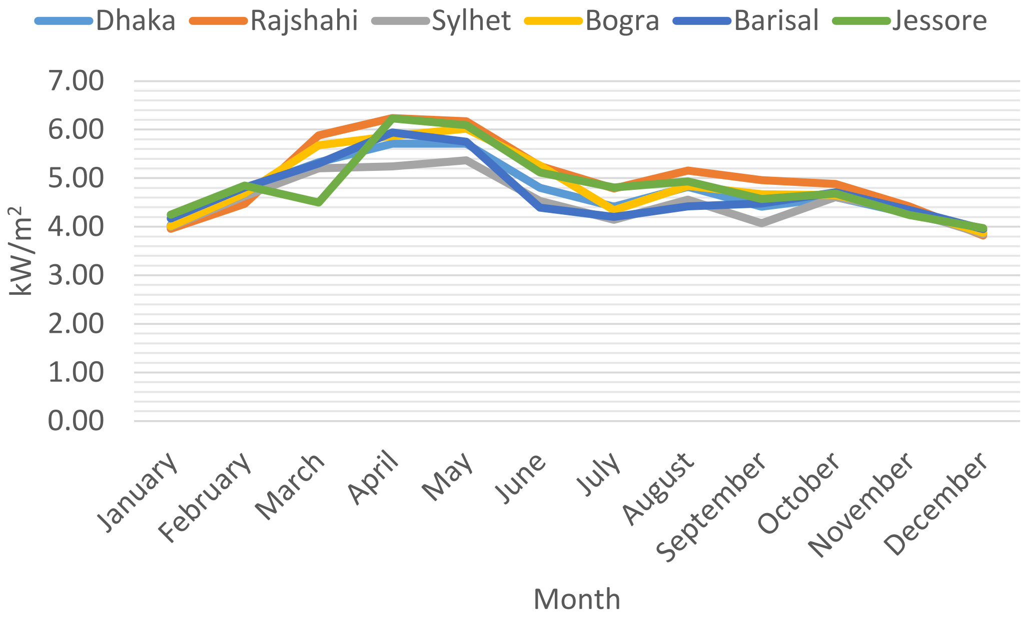

Fig. 2.5 Average monthly solar irradiation in Bangladesh [32].

2.2.2.1 Concentrating solar power (CSP) technology

Solar energy harnessing technology, for instance, concentrating solar power (CSP) could generate estimated 100 MW of electricity when annual average direct normal insolation (DNI) is about 2000 kWh/m^2 for a given area of 2 km^2 [55]. The average annual DNI that Bangladesh receives is about 1900 kWh/m^2 which is found sufficient in Rajshahi district to utilize such technology [56]. Even though, if such technology might have lagged to generate expected outcome, CSP–battery hybrid system can be introduced to meet such short deficit. Among the major CSP technologies developed such as, parabolic trough, parabolic dish, solar tower and Linear Fresnel Reflector (LFR); parabolic trough and parabolic dish are found theoretically suitable for Bangladesh environment [55], however substantial investment from GOB and other developing partners are required to harness full potential of such solar energy technology in Bangladesh. Besides this high capital intensive technology which is relatively at research and development stage, some of the technologies found vividly successful in Bangladesh, such as SHS, solar PV, and solar cooker. There are about 61,500 solar PV systems and 260 hot box cookers have been installed in the rural, coastal and hill tracks area in Bangladesh by different non-government organizations (NGOs) and government institutions [47].

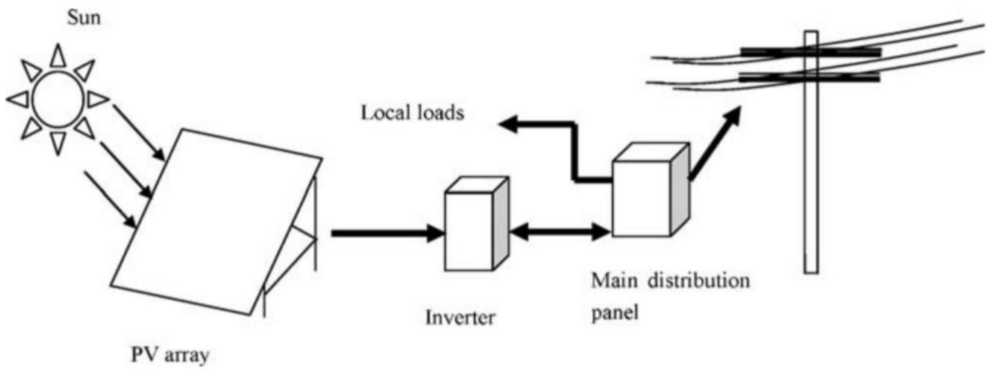

Fig. 2.6 Grid-connected PV power system with no storage [57].

2.2.2.2 Grid-connected solar PV system

The concept of grid-connected solar PV power system opened up new dimension of renewable energy utilization technique. It has the advantage of more effective and efficient utilization of generated power from PV array and main distribution line. Fig. 2.6 shows the arrangement of grid-connected solar PV power system with no storage [57]. Grid-connected PV system can be used in an integrated building system and native PV system. In Bangladesh, only 48.5% of the total population have grid connected electricity supply [58]. Bangladesh is at the nascent stage of implementing such kind of renewable energy harnessing technique. There is no commercial scale solar energy industry in Bangladesh and moreover, there is no coordinating authority for renewable energy sector in Bangladesh [47]. It was estimated that technical potential of grid-connected PV system in Bangladesh is around 50,174 MW [59]. Depending on the location of 14 districts of the country, it was calculated that annual electricity generation varies from 1653 megawatt hour to 1854 megawatt hour (MWh), with an average of 1729 MWh [59]. It is estimated that 500 kW grid connected solar PV system can reduce 658 tons of greenhouse gas [60]. Dhaka, capital of Bangladesh is the highest densely populated megacity in the world with more than 14 million populations [61]. Energy crisis has become an important issue, particularly in the urban areas. Existing roof tops present in the Dhaka city can produce 1000 MW of electricity generation, estimated by an individual 75-watt power (W) PV system setup [61]. Currently, Dhaka city is facing tremendous challenge to meet 1000–1200 MW power shortage against 2000 MW peak demand [61]. Adequate policy should be taken to promote roof-top solar PV and grid connected solar PV system in the urban areas mitigating future electricity demand. In rural Bangladesh, health care system is not well organized and power crisis in the hospitals is a usual phenomenon which is considered as a barrier utilizing modern health care services. Solar PV system can play an important role to mitigating such power crisis. Some of international NGOs, for instance, Bangladesh Rural Advancement Committee (BRAC) installed solar PV system in their rural branch offices, health clinics and training centers [62]. According to the authors in [41], grid-connected solar PV system needs substantial strategic refinement in future addressing "*With respect to the future, the most important perception is, with looming grid parity, a major challenge will be to link incentives for the effective own use of PV with market-based prices for feeding PV electricity into the grid. This investigation is left for future research work.*" As grid-connected solar PV system study is relatively new in Bangladesh, collaborative research partnership with the institute or organization from successful country can make positive and directional research outcome in the Bangladesh context. Smart grid – proposed by Chowdhury et al. [2] could be a cost effective and highly reliable hybrid energy system for rural and areas in Bangladesh. Moreover, minimizing cost and reduction in size and weight are required for more utilization of grid-connected solar PV system. Green entrepreneurship can be developed which will create new opportunity by manufacturing low cost PV array panel and other important components, such as inverter.

2.2.2.3 Solar home system (SHS)

SHS achieved remarkable success as off-grid power generation at rural and remote areas for domestic and small businesses [63]. The installed capacity of SHS is increasing at promising pace. As of 2015, numerous government and non-government organizations installed 3,863,964 SHSs, with installed capacity of 166 MW electricity [64]. Among the organizations, Grameen Shakti (GS) installed 1,622,865 which is the highest. Table 2.2 shows summary of SHS installation up to 2015 in Bangladesh by partner organizations [65]. Fig. 2.7 shows total number of SHS installed in different parts of Bangladesh [39]. The highest and lowest numbers of SHSs have been installed in Sunamganj and Patuakhali district which are 226,624 and 205,702, respectively. Up to January 2019, about 4.13 million SHSs have been installed under the program in the remote areas where electrification through gird expansion is challenging and costly. Thus the program has ensured supply of solar electricity to 18 million people i.e. 12% of the country's total population who previously used kerosene lamps for lighting purpose. IDCOL has a target to finance 6 million SHS by 2021 with an estimated generation capacity of 220 MW of electricity [14]. In the absence of adequate power supply, rural life style was less productive

Table 2.2 Dissemination of SHSs by different organizations in Bangladesh [64]

Organization IDCOL's PO	Number of SHSs Installed	Capacity
GS	1,622,865 SHSs all over the country	10-130 Wp each
RSF	566031 SHSs all over the country	
BRAC	77,279 SHSs all over the country	40 Wp (20%) 50 Wp (60%) and 75 Wp (20%)
Patakuri	77,279 SHSs	30-75 Wp each
Srizony Bangladesh	121,851 SHSs	
HFSKS	154.559 SHSs	
UBOMUS	25,234 SHSs	
BRIDGE	20,449 SHSs	
IDF	14.238 SHSs	
TMSS	13.059 SHSs	
PDBF	10.672 SHSs	
SEF	115,919 SHSs	
AVA	77,279 SHSs	
DESHA	10931 SHSs	
BGEF	115,919 SHSs	
RDF	115,919 SHSs	
COAST Trust	6181 SHSs especially in coastal areas	
INGENI Ltd.	9871 SHSs	
NUSRA	9372 SHSs	
RIMSO Foundation	8196 SHSs	
GHEL	6138 SHSs	
SFDW	9485 SHSs	
Government organizations		
LGED	SHSs, centralized units, and water pump in different remote and coastal off-grid areas all over the country	53.84 kW
BPDB	1212 51-155 at off-grid Hill areas. 6 solar vaccination refrigerators, 3 solar water pump. 30 solar street light. 4 centralized solar PV power plant at juraichari upazilla	374.26 kW
REB	23,412 SHSs and Solar Power Plants	1937.855 kW
BCSIR	82 SHSs, 1 pump, 2 solar data logging units	1.5 kW
Total	About 3,863,964 SHSs/SHLSs with 193 solar irrigation pump, solar central unit of total capacity 166 MW	

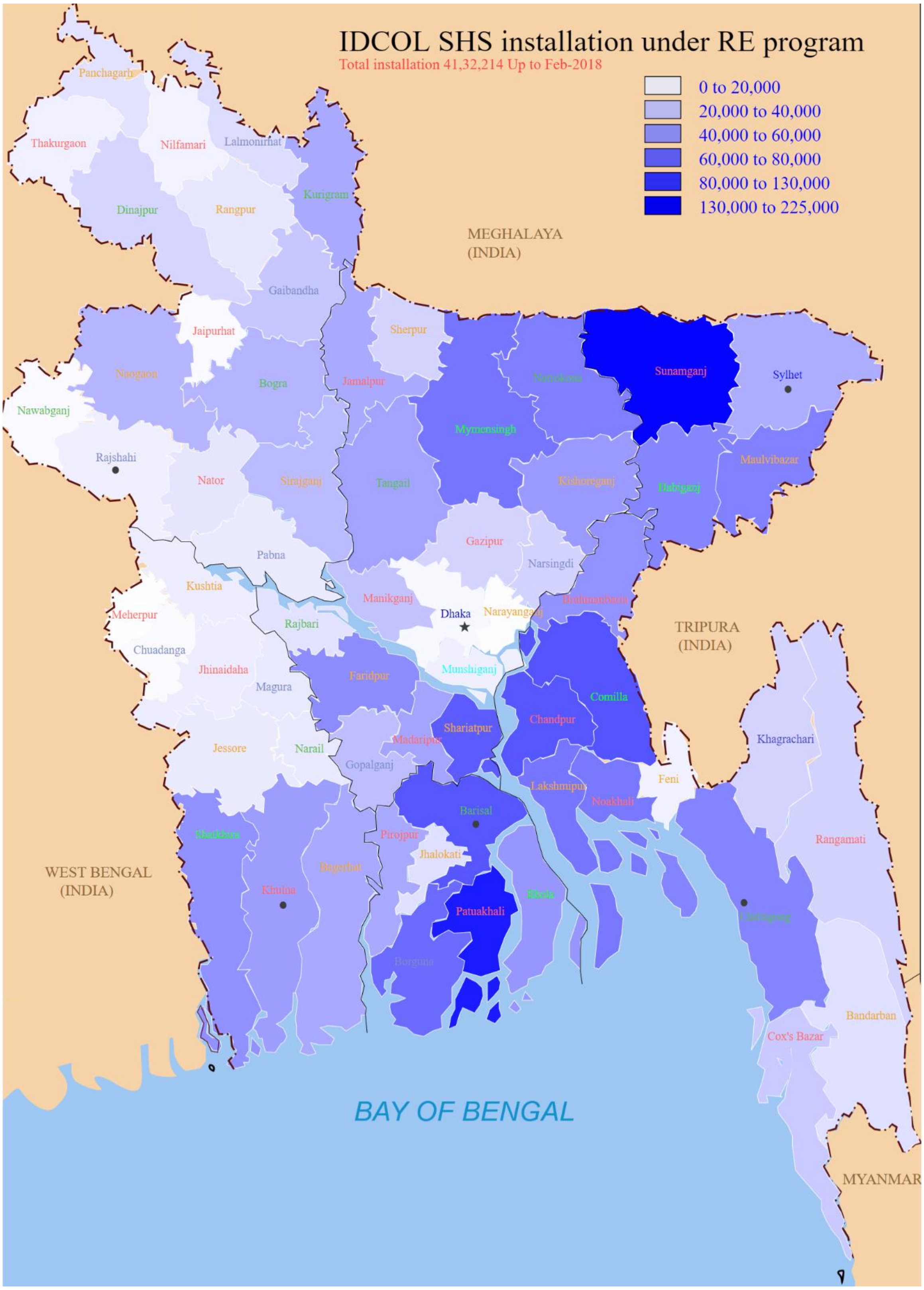

Fig. 2.7 Total number of SHS installed in different parts of Bangladesh upto Feb-2018 [39].

in terms of income generation and extended working hour. SHS showed promising contribution not only in electricity generation but also creating jobs and alleviate poverty. However, SHS should not be considered as comprehensive alternative poverty reduction tool for a country like Bangladesh, but it attributes to noticeable social benefit and change in livelihood in rural Bangladesh [59]. Green entrepreneurship as well as employment in the renewable energy sector can be developed through marketing and promotion. Solar energy has a numerous potential which can be tapped with appropriate technology in the context of Bangladesh [36]. Grid-connected solar PV has the highest potential in utilizing solar energy. However, as a decentralized system, SHS is a promising technology that can extend in rural Bangladesh proving subsidies and large scale investment from government and nongovernment organization. Furthermore, research conducted by Nandi and Ghosh [65] showed that a wind–PV–battery hybrid system can produce approximately 89,151 kWh/year in which 53% of electricity is coming from wind and solar energy, which is considered as a promising technological innovation for decentralized electricity generation in remote areas [65]. Besides, electricity generation, solar energy can be used as solar air heater for space heating [66]. Similar and further modified setup should be utilized drying rice and other agricultural products in the context of Bangladesh. For cooking purpose, solar cooking system has distinct advantages over conventional concentrators and box cookers, when evacuated tube collectors have been implemented in design [67]. Grameen Phone (GP), the largest mobile phone operator in Bangladesh, installed two PV–diesel hybrid systems with 8.05 kWp each, for power supply to their off grid Base Transceiver Station (BTS) in Hobiganj district while planning to install 12 more hybrid systems across the country [27]. However, it is a fact that no ground measurement data exist for Bangladesh [68]. To achieve more renewable energy mix at the desired rate, GOB and other developing partners should clearly take action against this technological deficit.

2.2.3 Wind energy

Wind energy is one of the fastest growing renewable energy sector of present time [69]. Wind turbine is used to convert wind energy to electricity, pumping water and so forth. Production and consumption of wind generated electricity was nearly zero in the early 1980s. Electricity generation from wind energy has reached 957.9 TWh in 2016 where offshore and onshore are 41.6 TWh and 916.3 TWh respectively [33]. Globally, wind turbine installed capacity was 6.1 GW in 1996 that reached 563.93 GW in 2018. Wind turbine installed capacity was increased 49.31 GW only in year 2018. Wind energy currently accounts for 59.4 GW in Germany. On the other hand, the US and China represents wind power installed capacity of 279 GW. Asia became the top investor in renewable energy field, especially in wind turbine sector; among those China and India are at the top. The total installed capacity of wind turbine in China and India stood 184.7 GW and 35.3 GW, respectively in 2018 [33]. Wind energy potential is not encouraging except in some coastal areas of Bangladesh [28]. Bangladesh has a costal belt of around 724 km along the Bay of Bengal consists of several islands. However, commercial power generation from wind turbine requires adequate techno-economic evaluation [1], which is not readily available. On the other hand, a well-constructed wind map and ground data is essential for assessment harnessing wind energy potential [70]. Geographically, strong south–south-east monsoon wind comes from Indian Ocean enters into the coastal area of Bangladesh after a long distance traveling through Asia. Approximately, from March to September wind blows at an average speed of 3–6 m/s over Bangladesh [71]. Study conducted by the Bangladesh Meteorological Department (BMD) found average wind speed during study period of 1991–1993 [47]. Global wind data and research shows that wind speed not more than 7 m/s is not viable for large scale grid connected electricity production within wind parks [47]. In most cases, measured values of wind speed are not present in Bangladesh. Up to present, several study conducted by Bangladesh Center for Advance Studies (BCAS), BMD and Local Government Engineering Department (LGED) revealed that wind speed varies from 2.96 to 4.54 m/s at a height of 25 m and 50 m in different parts of the country [47]. From literature, it is found that total wind turbine installed capacity in Bangladesh, varies from 20 kW to 50 kW [28,72]. Besides, LGED is actively engaged in manufacturing low cost pumps. Prototype based pumps can lift 20,000 l of water per day by average wind speed of 4 m/s. In total 6 prototypes have been installed in the country [28]. Global wind energy is growing at an expanding rate due to eco-friendliness and bulk power generation capabilities. Bangladesh is on its footstep to harness wind energy potential. At present, wind mapping and necessary ground data should be acquired to assess the full potential of wind energy. Considering a vast segment of population who are out of on-grid electricity, wind energy can substantially provide off-grid power in remote areas [73]. Affordable and reliable solar photovoltaic technology as well a durable and economic battery production would be an effective strategy for disseminating renewable energy in the rural electrification [74]. More research and development in the area should be conducted with comprehensive analysis, based on geographical context of Bangladesh.

2.2.4 Small scale hydro power energy

Worldwide, small-scale hydropower became popular because of low cost, reliability and environmental benefits. Globally, renewable energy contributed 2348.4 GW of electricity as of 2018, where hydropower accounts for 48% of the total renewable energy production [33]. Due to geographical flatness, Bangladesh has limited hydropower potential [28]. However, research findings show that in the existing geographical location, approximate hydro power potential is about 500 MW out of which, small scale hydropower plants have potential to generate electricity of 5 MW [31-32]. Potential sites for hydropower have been discovered at Chittagong Hill Tracks (CHTs) area, and river basin of Matamuhuri and Sangu. Exploration and feasibility studies have been carrying out since 1981 by Bangladesh Water Development Board (BWDB) and Bangladesh Power Development Board (BPDB) of GOB. Definition of small scale hydropower varies depending on available heads and generation capacity. Micro-hydro power can generate 5–300 kW of electricity [75]. A list of potential sites of small scale hydropower found from the studies is summarized in Table 11 [71]. In 2008, LGED reported several potential sites for micro-hydro power plant with a power generating potential up to 30 kW [76]. Moreover, sustainable rural energy (SRE) has identified potential sites in the CHT areas in 2004 for micro-hydro power plants. Among the micro-hydro sites, Bemerchara showed prospect of electricity generation capacity of 4 kW [29]. More feasibility study should be carried out to harness full potential of small scale hydro energy in Bangladesh. Most of the small scale hydro power potential sites were discovered in rural, remote and hill tracks areas of the country which can contribute to overall socio-economic development of the country ensuring power supply for the rural population.

2.3 Renewable energy policy in Bangladesh

A draft renewable energy policy of Bangladesh was released in 2002. This draft policy provided modalities and procedures, tariff regulations, fiscal and other incentives for implementation of RETs and guidelines for establishment of an independent renewable energy authority, namely the Renewable Energy Development Authority [30,77]. This draft renewable energy policy was revised and finalized by the Ministry of Power, Energy, and Mineral Resources (MPEMR) in December 2008 [30,78]. The policy is not effective yet; it will become effective from the date of publication in the official gazette. The main objectives of the renewable energy policy are [30,78]:

(i) to harness the potential of renewable energy resources and dissemination of RETs in rural and urban areas;

(ii) to enable, encourage and facilitate both public and private sector investment in renewable energy projects;

(iii) to develop sustainable energy supplies to substitute indigenous non-renewable energy supplies;

(iv) to scale up the contribution of renewable energy to electricity production;

(v) to facilitate the use of renewable energy at every level of energy usage;

(vi) to promote development of local technology in the field of renewable energy;
(vii) to promote clean energy for clean development mechanism (CDM).

The MPEMR of Bangladesh is the sole authority administering all activities related to energy, including rural and renewable energy. Although establishment of REDA was proposed in 2002 in the draft policy, by the end of 2005, the government of Bangladesh decided to establish an alternative independent unit, the Sustainable Energy Development Authority (SEDA) instead of REDA for expediting the use of renewable energy for power generation [79]. In the renewable energy policy (REP) of 2008, the government of Bangladesh again recommended to set up an organization called SEDA, to be established under the Companies Act of 1994. The SEDA board will comprise of representatives of stakeholders, including business community, academics, and/or representative from Bangladesh solar energy society, NGOs, financial institutions, and implementing agencies. The main responsibilities of SEDA as a company shall be:

(i) to provide coordination of sustainable energy planning, including action plans linking together activities of several agencies or organizations;

(ii) to promote awareness of renewable energy and other clean energy technologies and integrate their development within overall national energy policy and development;

(iii) to support demonstration of new technologies and new business models for renewable energy and other clean energy technologies;

(iv) to support establishment of small and medium renewable energy enterprises and providers;

(v) to create market opportunities and start-up business models for sustainable energy technologies;

(vi) to develop financing mechanisms and facilities by using grant, subsidy and/or carbon/CDM fund for public and private sector investments;

(vii) to collect data and assess the renewable energy resources potential, especially in the context of rural energy master plan.

Salient features of the renewable energy policy [30,78] on resource, technology, and program development are:

(i) SEDA in conjunction with the power division of the MPEMR shall be responsible for determining the priorities for RET development and program implementation;

(ii) SEDA shall support capacity building, technology development, and market development sufficient to boost the share of electricity generated from RETs;

(iii) all power utilities, the Local Government Engineering Department (LGED), other interested government departments, private agencies and NGOs are to develop renewable energy development program for implementation throughout the country;

(iv) electricity generated from renewable energy projects may be purchased by power utilities;

(v) renewable energy project sponsors may use existing electricity transmission and distribution systems and the wheeling charges shall be determined by the Bangladesh Energy Regulatory Commission (BERC) in consultation with the power division of MPEMR;

(vi) in addition to electricity generation, renewable energy for solar heating and biogas or other means like cooking etc. shall be developed.

2.4 Microgrid

Microgrids are now used widely, to manage the addition of distributed clean energy resources like small scale hydro, wind and solar photovoltaic (PV) generation to reduce fossil fuel emissions, to improve reliability and resilience of electrical grids, and to provide electricity in areas not served by centralized electrical infrastructure [80]. The concept of microgrids dates back to 1882 when Thomas Edison built his first power plant. Edison's company installed 50 DC microgrids in four years. At that time centrally controlled and operated utility grids were not yet formed. With the utility grid subsequently utilizing large centralized power plants which benefited from the economies of scale, and significantly increasing transmission connections for reliability purposes, the electric grid turned into a monopolistic utility by connecting isolated microgrids, and these microgrids faded away. The use of microgrids is on the increase, which is driven in part by the need for higher reliability and power quality, advancements in power electronics and DER technologies, and a more engaging generation of electricity consumers [81].

A number of microgrid definitions [82] and functional classification schemes [83] can be found in the literature. A broadly cited definition, developed for the U.S. Department of Energy by the Microgrid Ex-change Group, an ad hoc group of research and deployment experts, reads as follows: ''A microgrid is 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 connect and disconnect from the grid to enable it to operate in both grid-connected or island mode" [84].

This description includes three requirements: 1) that it is possible to identify the part of the distribution system comprising a microgrid as distinct from the rest of the system; 2) that the resources connected to a microgrid are controlled in concert with each other rather than with distant resources; and 3) that the microgrid can function regardless of whether it is connected to the larger grid or not. The definition says nothing about the size of the distributed energy resources or the types of technologies that can or should be used.

2.5 AC vs DC microgrids

The efficiency gains associated with using a DC architecture for household settings has been explored in the context of integrating renewable resources and electric vehicles in countries with a strong central grid architecture [85-86]. However, the case for deploying DC microgrids in rural emerging regions is even stronger due to the combination of the following factors:

(i) There are many advantages of using solar PV for distributed generation in rural emerging regions such as:

(a) Availability of solar resource in regions with low electricity-access
(b) The low cost of PV as a generation source
(c) The modularity and ease of transport of PV panels

(ii) The predominant usages of rural off-grid customers—lighting, cell phone charging, fans—come from DC appliances.

Studies suggest that a 20% cost-reduction is possible through gains associated with improved power-conversion efficiencies that can be realized with a fully functional DC microgrid [87]. Distributed point-of-load (POL) converters can achieve higher efficiencies than always- on central inverters; POL converters can be selectively turned off, and thereby reduce standby electricity-losses in the grid. The potential efficiency improvements of a solar- powered DC microgrid compared to an equivalent AC microgrid are shown in Figure 2.8. Some of the main factors that influence the efficiency calculations shown in Figure 2.8 are:

(i) In an AC microgrid with a centralized battery bank, there is a constant source of loss due to the always-on inverter. In a DC microgrid with distributed storage, this loss is mitigated during nighttime as the DC distribution is off at night.

(ii) A majority of end-use appliances are inherently DC devices. The losses from POL AC-DC adapters have been estimated to be around 15% [88]. This is energy that is lost without any end-use benefit.

(iii) In an AC microgrid, inverter losses can dominate with mismatch in rated-power to actual load. The size of the inverter (kVA-rating) is determined by the peak power-load expected. There have been numerous microgrid studies that show that peak loads are correlated in time across many households. Examples of such loads are electric rice cookers and electric kettles running at the same time of the day. Inverters that are sized to match the average power demand are unable to mitigate these correlated peaks in demand and this mismatch leads to grid-wide brownouts. In a DC microgrid with distributed storage, the batteries function as local energy buffers that filter variability in power-demand on upstream power converters.

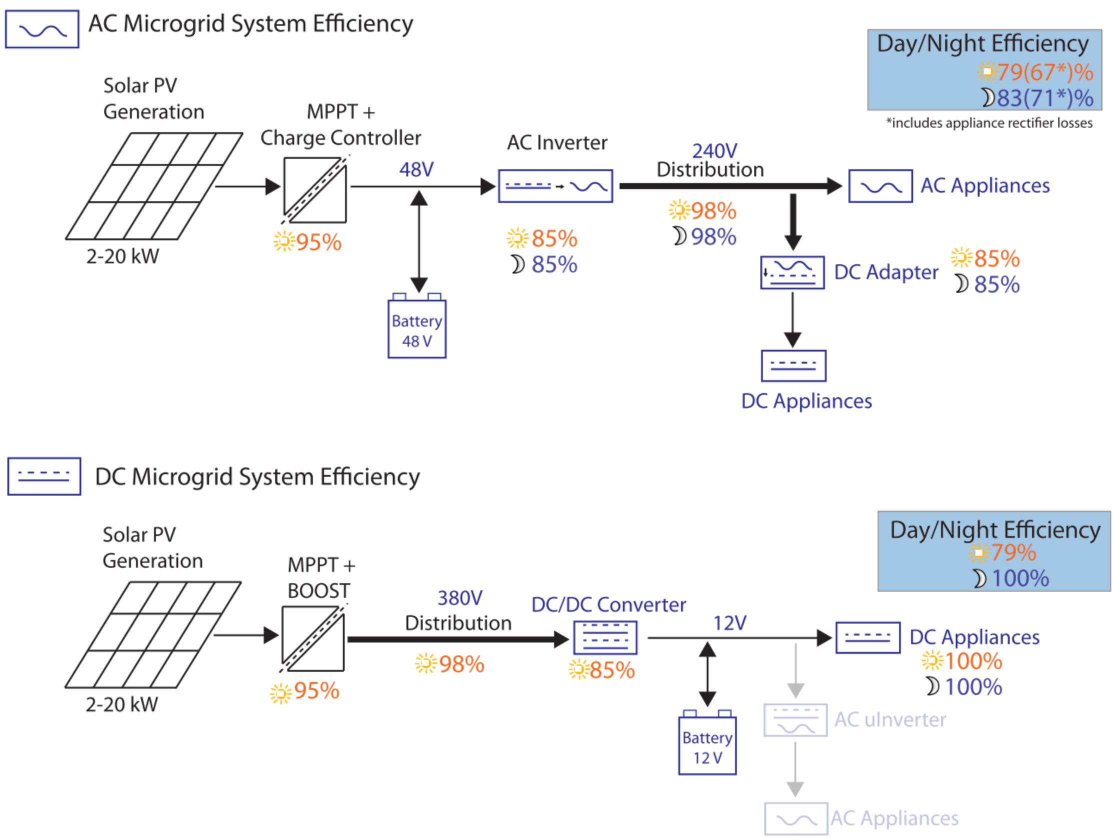

Fig. 2.8 AC vs DC microgrids day/night efficiency. Since the efficiency of stored power is an important figure of merit, the ability to distribute storage in a DC system allows for minimizing conversion steps on stored electricity [88-90].

(iv) On the other end of the spectrum, when the average power demand is substantially below peak in an AC microgrid, inverter efficiencies suffer. This is due to the fact that inverter efficiencies are highest when operating between 80-90% of rated output capacity. [69] When inverters are operated at low utilization-rates (average- load/rated-capacity), the overall efficiencies of AC microgrid suffer. When storage is distributed, the upstream power converters can be sized to better match average demand and hence operate at higher efficiencies. It is possible to easily distribute storage in DC microgrid.

(v) In addition, it is generally hard to resize AC microgrids incrementally. The lack of an inverter and centralized-storage makes it easy to incrementally add more generation in a DC microgrid with distributed storage.

2.6 DC Microgrid Architecture

The PV array acts as a constant current source. In the dc microgrid architecture, the photovoltaic array (PV Array) is model as [91]

$$I = I_{pv} - I_0 \left[e^{\frac{V+R_S}{aV_t}} - 1 \right] - \frac{V+R_S}{R_p} \qquad (1)$$

where I_{pv} and I_0 are the photovoltaic (PV) and diode saturation currents, respectively, of the array and $V_t = N_s kT/q$ is the thermal voltage of the array with N_s cells connected in series. R_s and R_p are the series and parallel resistance as indicated in Fig. 2.9 while a is the diode ideality factor.

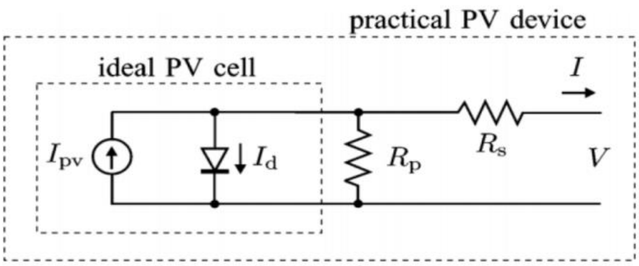

Fig. 2.9 Single diode model of a PV cell and equivalent circuit of a PV device with series and parallel resistances.

Basic Full Bridge Converter Based DC Microgrid Architecture is shown in Fig. 2.10. Based on irradiation level, the perturb and observation method tracks the maximum power point and generates the duty cycle required for the boost average DC-DC converter to level up the voltage. The PMU consists of a FB converter where MOSFETs are used as the switching devices. The main purpose is to monitor the equal and unequal load sharing of the PMUs and then generate an adaptive look up table for which the power source can be utilized accordingly. Initially only two PMUs are connected in the architecture

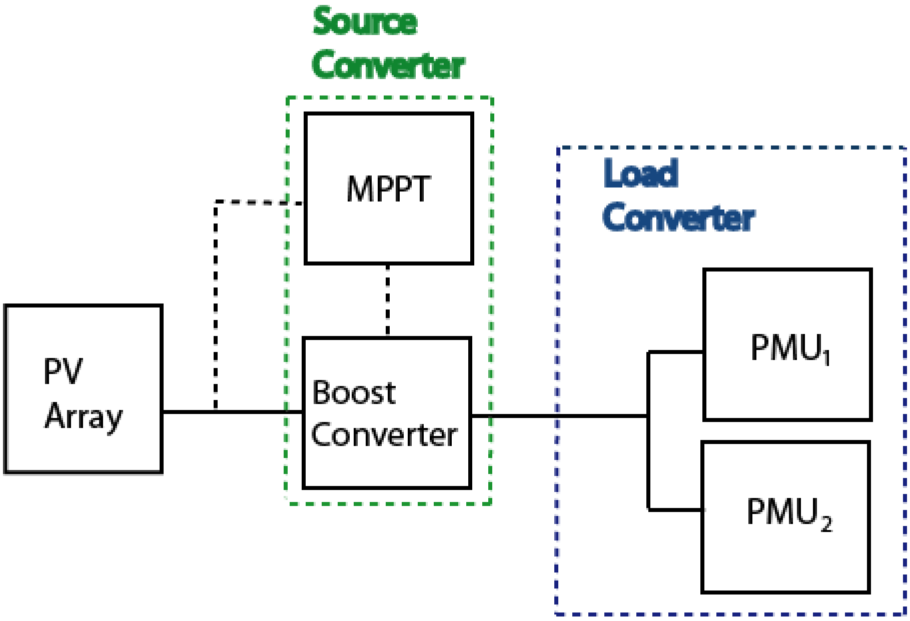

Fig. 2.10 Basic Full Bridge Converter Based DC Microgrid Architecture.

2.6.1 Perturb and Observation Algorithm based MPPT Control

Maximum Power Point Tracking (MPPT) is a methodology used in photovoltaic (PV) converters to continuously adjust the impedance seen by the solar array to keep the PV system operating at, or close to, the peak power point of the PV panel under varying conditions, like changing solar irradiance, temperature, and load as shown in Fig 2.11. The algorithm senses the voltage V(k) and current I(k) to measure the instantaneous power P(k) at the k^{th} sample. Then it compares it with previous power sample P(k-1). If the two power samples are different then it then the voltage sample V(k) is compared with its previous sample V(k-1) and the duty cycle D_b of the boost converter is adjusted accordingly to ensure that the system operates at maximum power point (or peak voltage) on the power voltage curve, as shown below. The algorithms account for factors such as variable irradiance (sunlight) and temperature to ensure that the PV system generates maximum power at all time

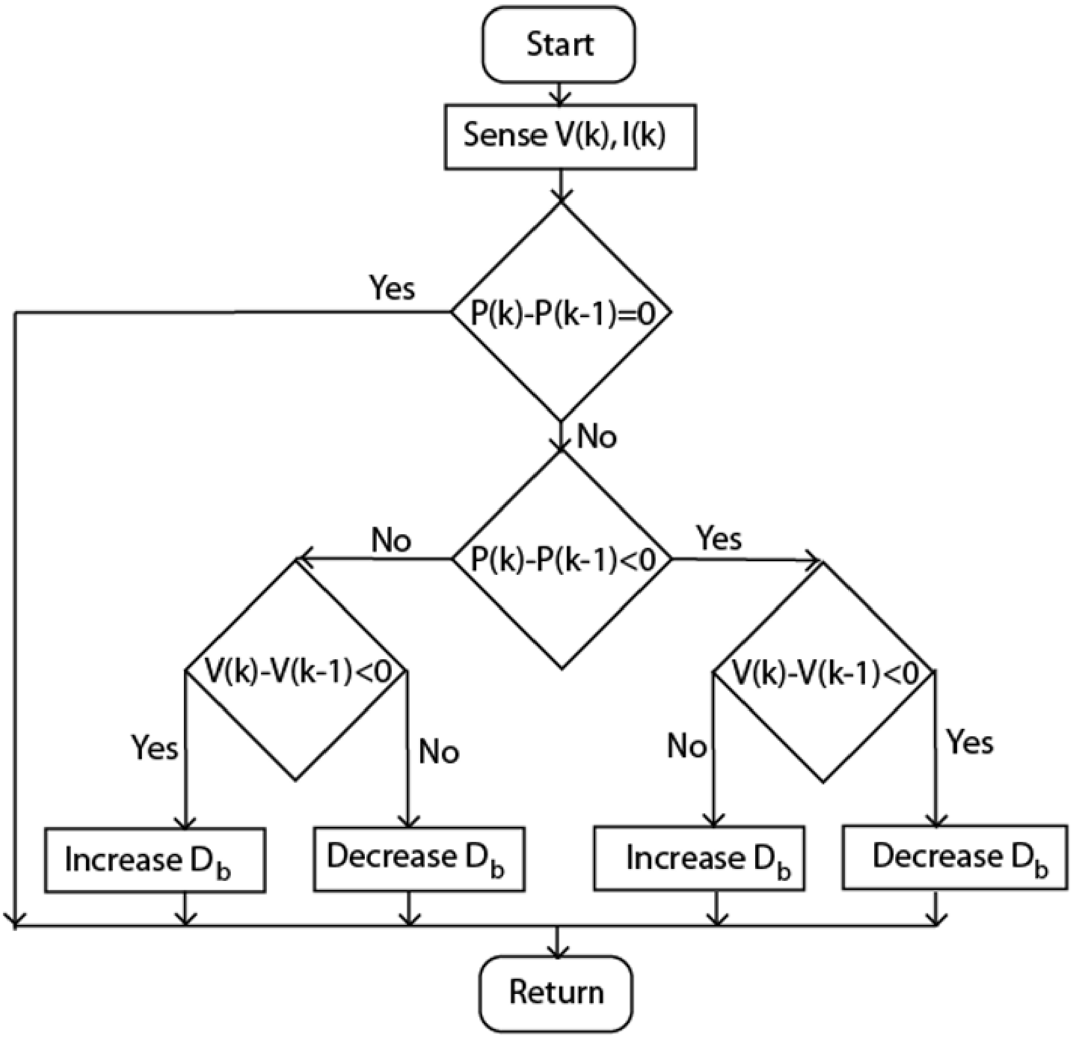

Fig. 2.11 Perturb and Observation Algorithm.

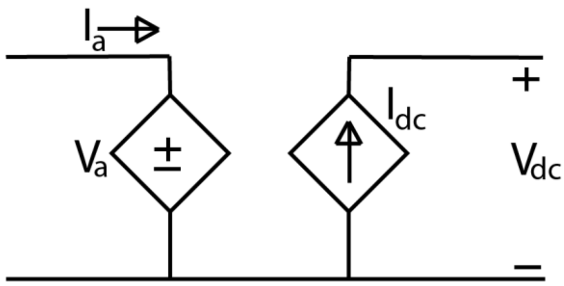

Fig. 2.12 Boost converter average model [92].

2.6.2 Boost Converter Average Model

The average model for boost converter is designed with a controlled voltage source in the input and a controlled current source in the output. In Fig. 2.12, V_a and I_a are the input current and voltage whereas V_{dc} and I_{dc} are the output current and voltage of the boost converter. The equations for V_a and I_{dc} are

$$V_a(k) = (1 - D_b)V_{dc}(k-1) \tag{2}$$

$$I_{dc}(k) = \frac{(1-D_b)V_{dc}(k-2)I_a(k-1)}{2V_{dc}(k-2)-V_{dc}(k-3)} \tag{3}$$

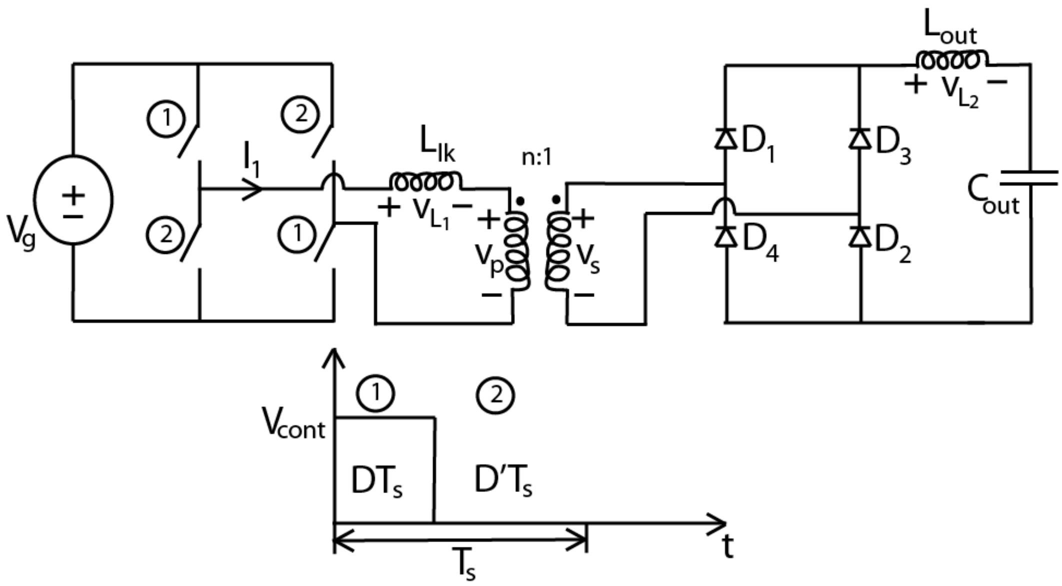

Fig. 2.13 Circuit diagram of the PMU Block and the control switch pattern [92].

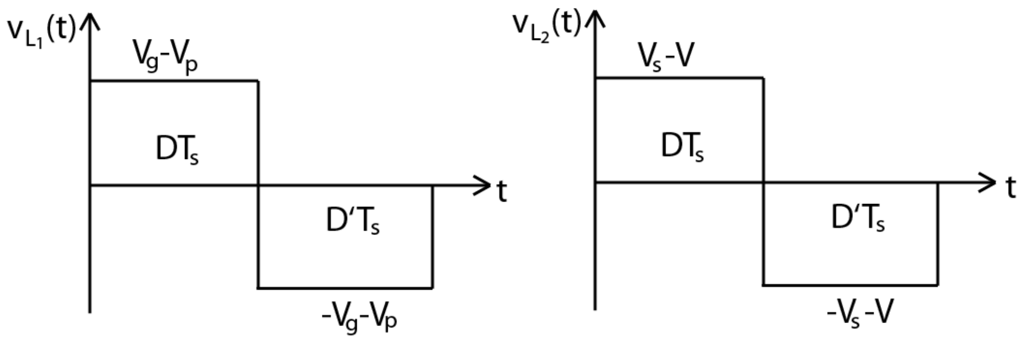

Fig. 2.14 Inductive voltage pattern considering ideal active and passive switches [92].

2.6.3 PMU Circuit Operation Analysis

2.6.3.1 Ideal Active and Passive Switches

The MOSFETs in the PMUs are the active switches and each has an internal diode paralleled with a RC snubber circuit. When a gate signal is applied to the MOSFET it acts as the switch on-resistance and when the gate signal is turned off the current moves through the anti-parallel diode. V_g is the input voltage for the PMUs and the control switch are delineated as 1 and 2 inside a circle in Fig. 2.13. A linear transformer is used to lower the voltage into desired level as well as provide electrical isolation. The four diodes D_1, D_2, D_3 and D_4 are the passive switches. The L_{lk} models the leakage inductance and has a damping effect on the circuit. The change in current through the output inductor L_{out}, and the change in voltage across the output capacitor C_{out} are small compared through their nominal values over a switching period [25,93]. Considering the control switch pattern in Fig. 2.13, D+D` = 1 at switch position 1 during DTs subinterval

$$V_{L_1} = V_g - V_p \text{ and } V_{L_2} = V_s - V \quad (4)$$

at switch position 2 during D`Ts subinterval

$$V_{L_1} = -V_g - V_p \text{ and } V_{L_2} = -V_s - V \quad (5)$$

in both cases, small ripple approximation is considered here,

$$V_p = nV_s \quad (6)$$

Using volt-sec balance for inductor L_{lk} and L_{out} taking equation (4), (5) and (6) as shown in Fig. 2.14

$$(V_g - nV_s)D + (-V_g - nV_s)D` = 0$$

$$V_s = \frac{1}{n} V_g(2D - 1) \quad (7)$$

$$V_s(2D - 1) = V$$

from (7), voltage gain,

$$M(D) = \frac{V}{V_g} = \frac{1}{n}(2D - 1)^2 \quad (8)$$

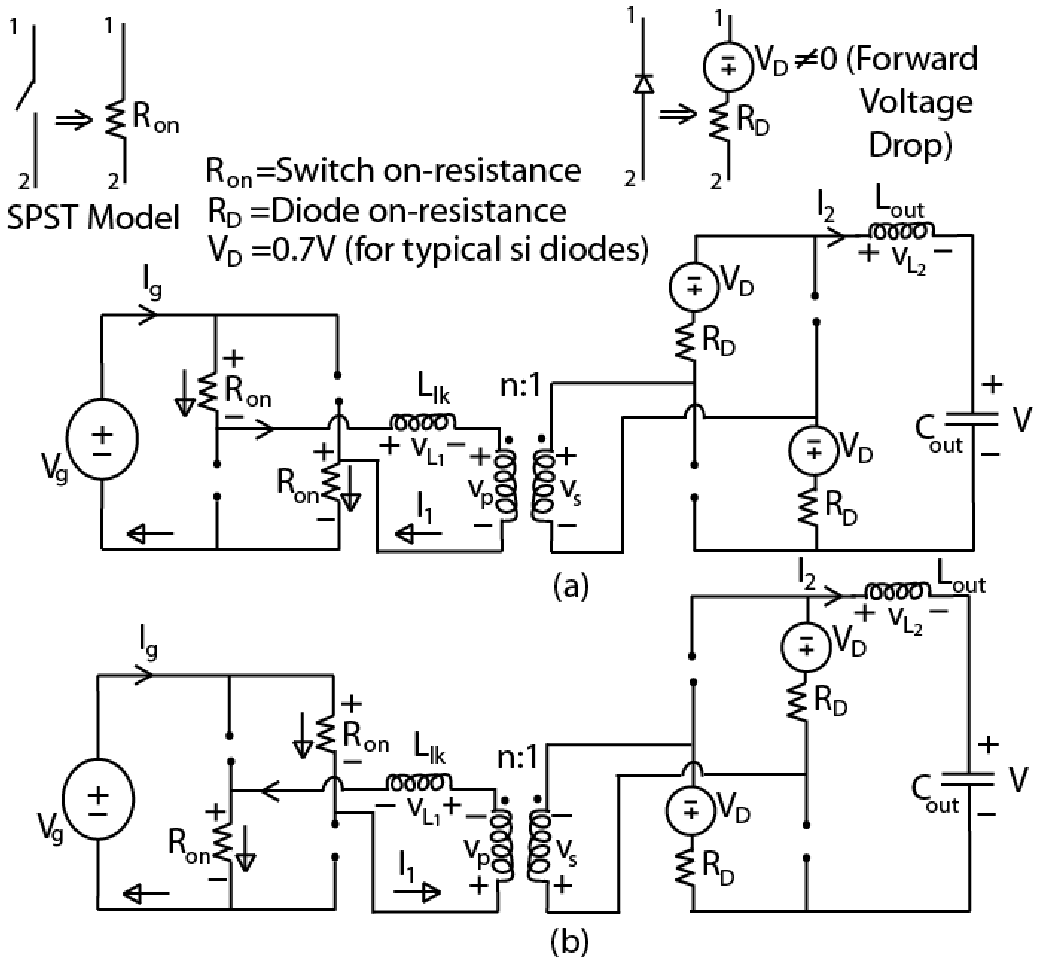

Fig. 2.15 PMU circuit operation analysis considering non-ideal active and passive switches; (a) PMU in switch position-1 and (b) PMU in switch position-2 [92].

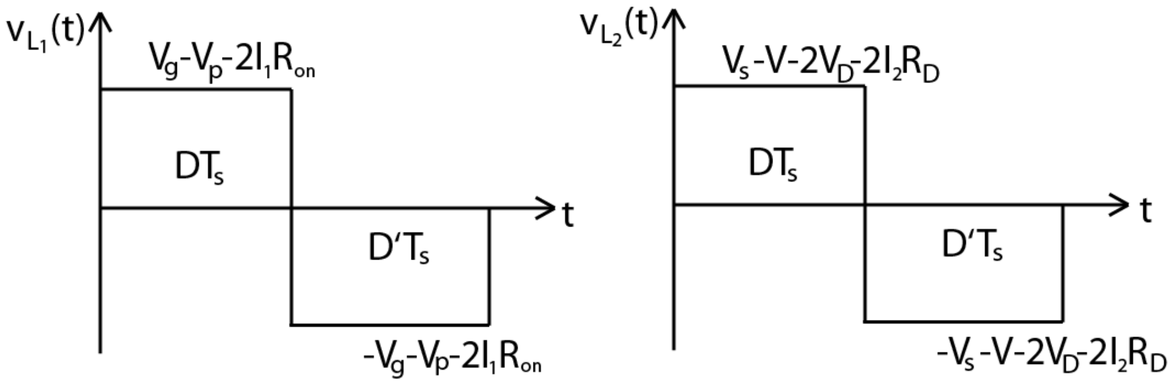

Fig. 2.16 Inductive voltage pattern considering non-ideal active and passive Switches [92].

2.1.3.2 Active and Passive Switches with Semiconductor Losses

At switch position-1 as shown in Fig. 2.15 and Fig. 2.16

$$V_{L_1} = V_g - V_p - 2I_1R_{on} \tag{9}$$

$$V_{L_2} = V_s - V - 2V_D - 2I_2R_D \tag{10}$$

At switch position-2 as shown in Fig. 2.15 and Fig. 2.16

$$V_{L_1} = -V_g - V_p - 2I_1R_{on} \tag{11}$$

$$V_{L_2} = -V_s - V - 2V_D - 2I_2R_D \tag{12}$$

Now using volt-second balance for L_1 and L_2 and $V_p = nV_S$ and $I_2 = nI_1$

$$(V_g - V_p - 2I_1R_{on})D + (-V_g - V_p - 2I_1R_{on})D` = 0$$

$$V_g(2D-1) - 2I_1R_{on} = nV_s$$

$$V_s = \frac{1}{n}\left[V_g(2D-1) - 2I_1R_{on}\right] \tag{13}$$

and

$$(V_s - V - 2V_D - 2I_2R_D)D + (-V_s - V - 2V_D - 2I_2R_D)D` = 0$$

$$V_s(2D-1) = V + 2V_D + 2I_2R_D$$

$$\frac{1}{n}\left[V_g(2D-1) - 2I_1R_{on}\right](2D-1) = V + 2V_D + 2I_2R_D$$

$$\frac{1}{n}V_g(2D-1)^2 = \frac{2}{n}I_1R_{on}(2D-1) + V + 2V_D + 2nI_1R_D \qquad (14)$$

From (14)

$$\frac{1}{n}V_g(2D-1)^2[1 - \frac{2I_1R_{on}}{V_g(2D-1)} - \frac{2nV_D}{V_g(2D-1)^2} - \frac{2n^2I_1R_D}{V_g(2D-1)^2}] = V$$

Now, voltage gain,

$$M'(D) = \frac{V}{V_g} = M(D)[1 - \frac{2I_1R_{on}}{V_g(2D-1)} - \frac{2nV_D}{V_g(2D-1)^2} - \frac{2n^2I_1R_D}{V_g(2D-1)^2}]$$

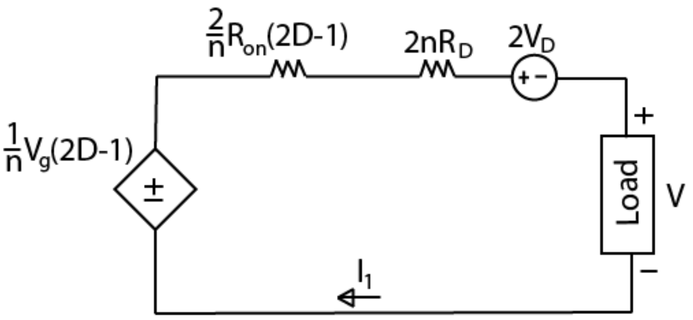

Fig. 2.17 Input-to-output port of the PMU circuit acting in non-ideal switching mode [92].

2.7 DC Microgrid Architecture with Two Stage Conversion at the Load Side

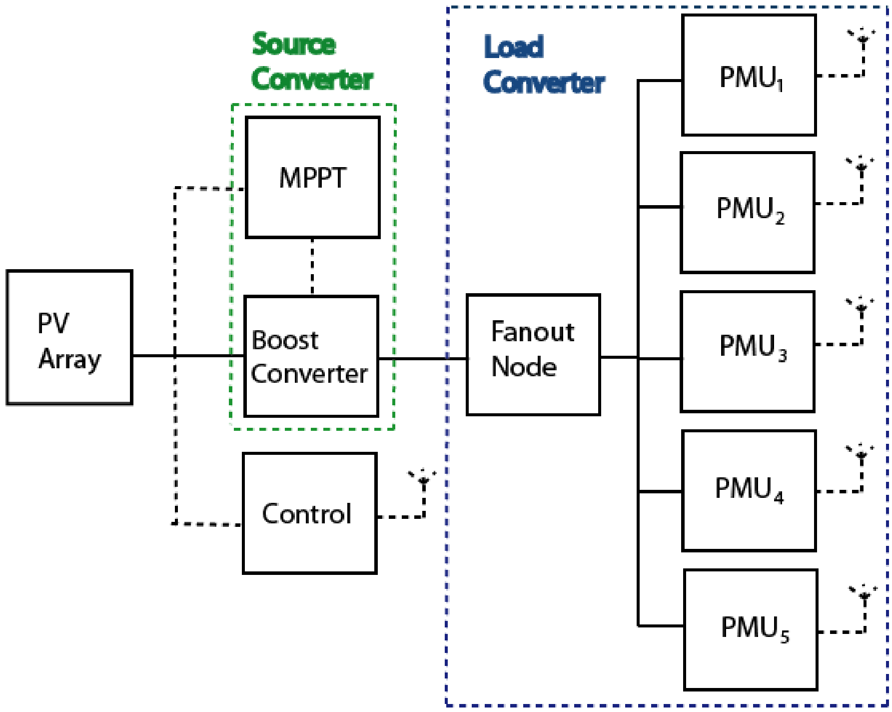

Fig. 2.18 DC microgrid architecture with Two Stage Conversion at the Load Side.

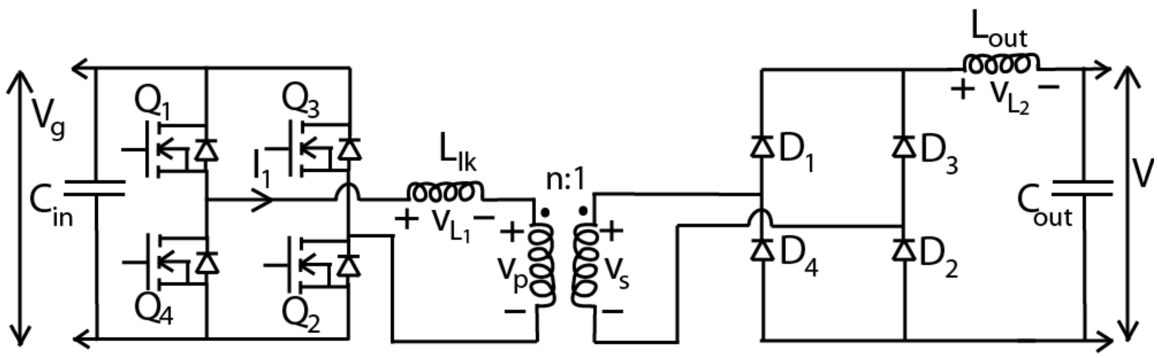

Fig. 2.19 Full Bridge Converter acting as Fanout node for Two Stage Conversion at the Load Side in DC microgrid architecture.

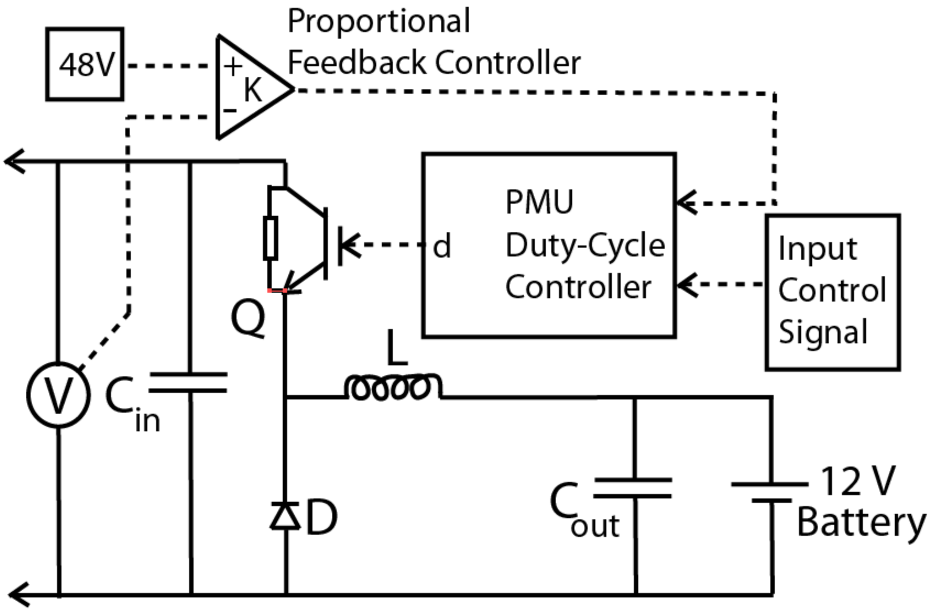

Fig. 2.20 Buck Converter circuit structure working as PMU for Two Stage Conversion at the Load Side in DC microgrid architecture.

The PV Array connected with a boost converter average model as described in 2.1.2. The duty cycle of the boost converter is adjusted by perturb and observation (P&O) method as described in 2.1.1. The P&O block and boost converter combinedly represent the source converter in Fig. 2.18. The output of the source converter is then reduced by a consecutive two-stage conversion process in the distribution side. At the first stage, a full bridge (FB) converter is used to reduce the voltage to 48 V which is denoted as the fanout node in Fig. 2.19. MOSFETs with internal parallel diodes are used as the active switches in the FB converter. A linear transformer reduces the voltage in a desired level as well as provides electrical isolation. Four diodes work as the passive switches and L_{lk} models the leakage inductance and has a damping effect on the circuit. The change in current through the output inductor, L_{out} and the change in voltage across the output capacitor, C_{out}, are small compared through their nominal values over a switching period [25,93].

Five identical PMUs are connected in parallel with the fanout node which is the second stage of conversion in the distribution side. Buck Converter circuit structure working as PMU as shown in Fig 2.20. The fanout node and PMUs jointly represent the load converter structure as depicted in Fig. 2.18. The input-output relationship of the buck converter inside the PMU can be defined as

$$\boldsymbol{V_o = d_c V_i}$$

here Vi, Vo and dc are the input voltage, output voltage and duty cycle of a PMU (buck converter) respectively.

2.8 Control Interface for DC Microgrid Architecture

A control interface is designed from the source side to the load side so that the uniform power management can be maintained in case of change in irradiance. The Control Interface has one input and five output as depicted in Fig. 2.21. The control signal takes irradiance level as input and generate five control signal to the PMUs. The PMUs are controlled by controlling the duty cycle of the IGBT as shown in Fig. 2.20. When proportional feedback controller gives a positive input and the input control signal is numeric one the PMU is in the ON state. And if the control signal is zero then the PMU is in OFF state. The input control signal is generated using the control algorithm for the five PMUs as illustrated in Fig. 2.22. When the irradiance is switched to lower value than the duty cycle of the PMUs, the proposed one-way control algorithm maintains balance among different PMUs. For instance, when the irradiance falls from 1000W/m^2 to 800W/m^2 the input control signal switches off the PMU1 keeping PMU2, PMU3, PMU4 and PMU5 switched on. And if the irradiance falls 800 W/m^2 to 600 W/m^2 the input control signal switches off the PMU1, PMU2 keeping PMU3, PMU4 and PMU5 switched on. But this algorithm has the fault that PMU1 and PMU2 will suffer most in case of fall of irradiance. Therefore, a control scheme should be implemented so the turn off time is divided among the PMUs equally in case of lengthy drop in irradiance.

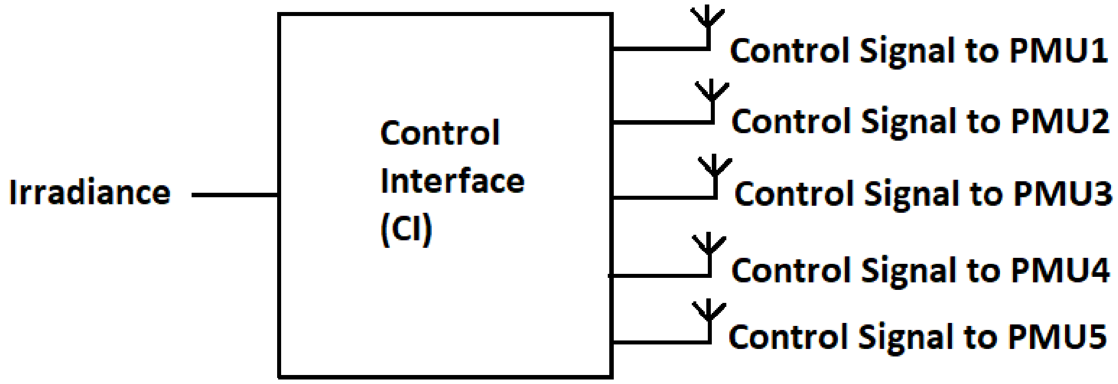

Fig. 2.21 Block Diagram of Control Interface.

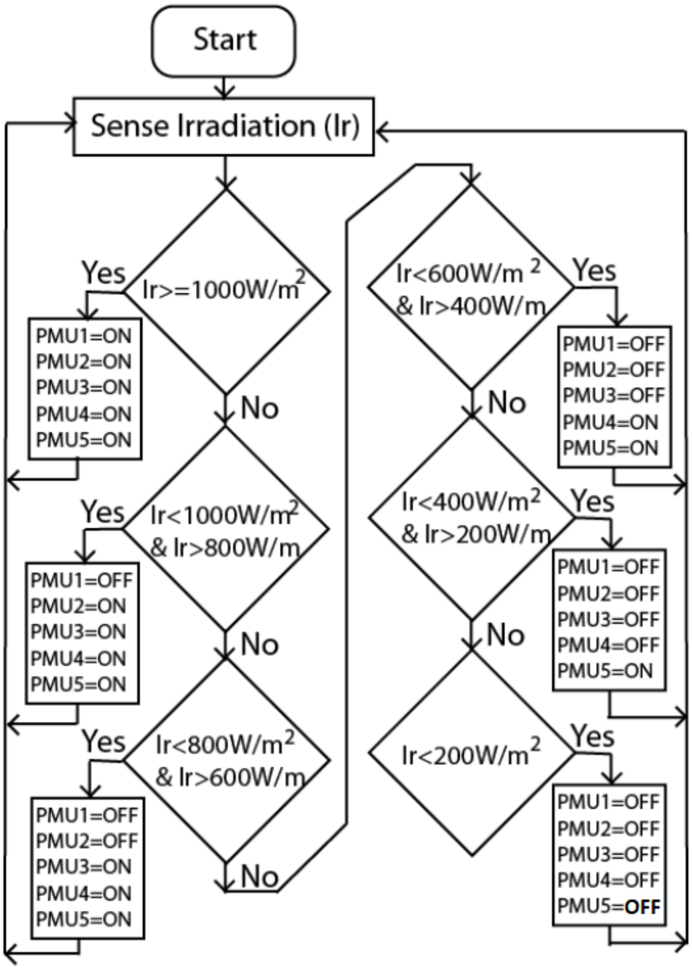

Fig. 2.22 Control algorithm of the Control Interface for five PMUs in the dc microgrid architecture.

2.9 Time Slot Based Control Scheme for DC Microgrid Architecture

This section has been divide into parts. At first modification of control interface for time slot based control scheme is described and then the control scheme is elaborated.

2.9.1 Modification of Control Interface for Time Slot based Control Scheme

For the time slot based control scheme, timer counter (TC) is used which has 4 inputs and 2 outputs as shown in Fig. 2.23(a). The inputs are Increment Condition (IC), Reset(R), Increment Value, Target Time (TT) and the outputs are Timer Value and Timer Status (TS). Moreover, the control interface is modified as Fig. 2.23(c). The Control Interface now takes feedback from TCs and also a reset signal is sent to TCs.

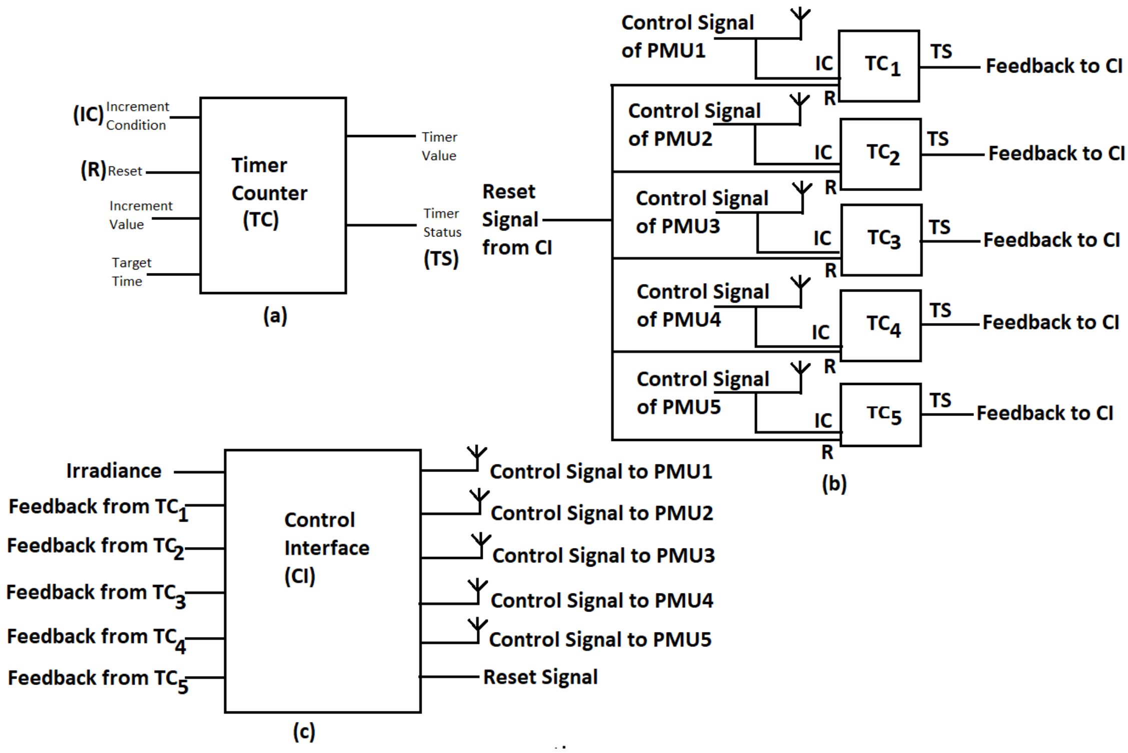

Fig. 2.23 (a) Block Diagram of Timer Counter (b) Connection Diagram in the DC Microgrid Architecture and (c) Modified Block Diagram of Control Interface for Time Slot based Control Algorithm.

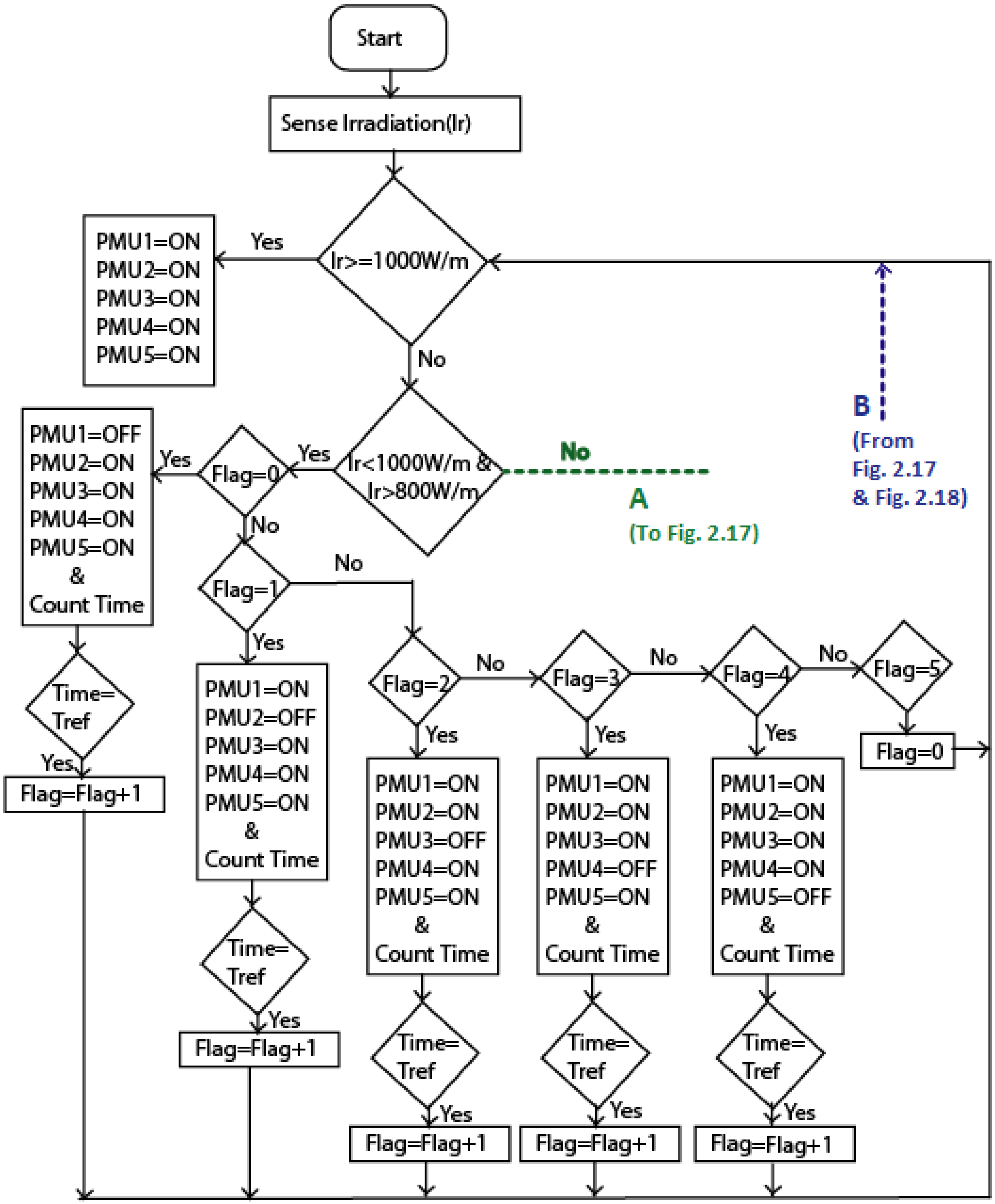

Fig. 2.24 Part 1 of Time Slot based Control Scheme for five PMUs in the dc microgrid architecture.

Five TCs are connected with the control signal of the five PMUs as shown in Fig. 2.23(b). The five control signal is connected with ICs of the five TCs. Each TC has a TS which is send as the feedback to the control interface. The reset signal from the CI is connected to the R of each TCs.

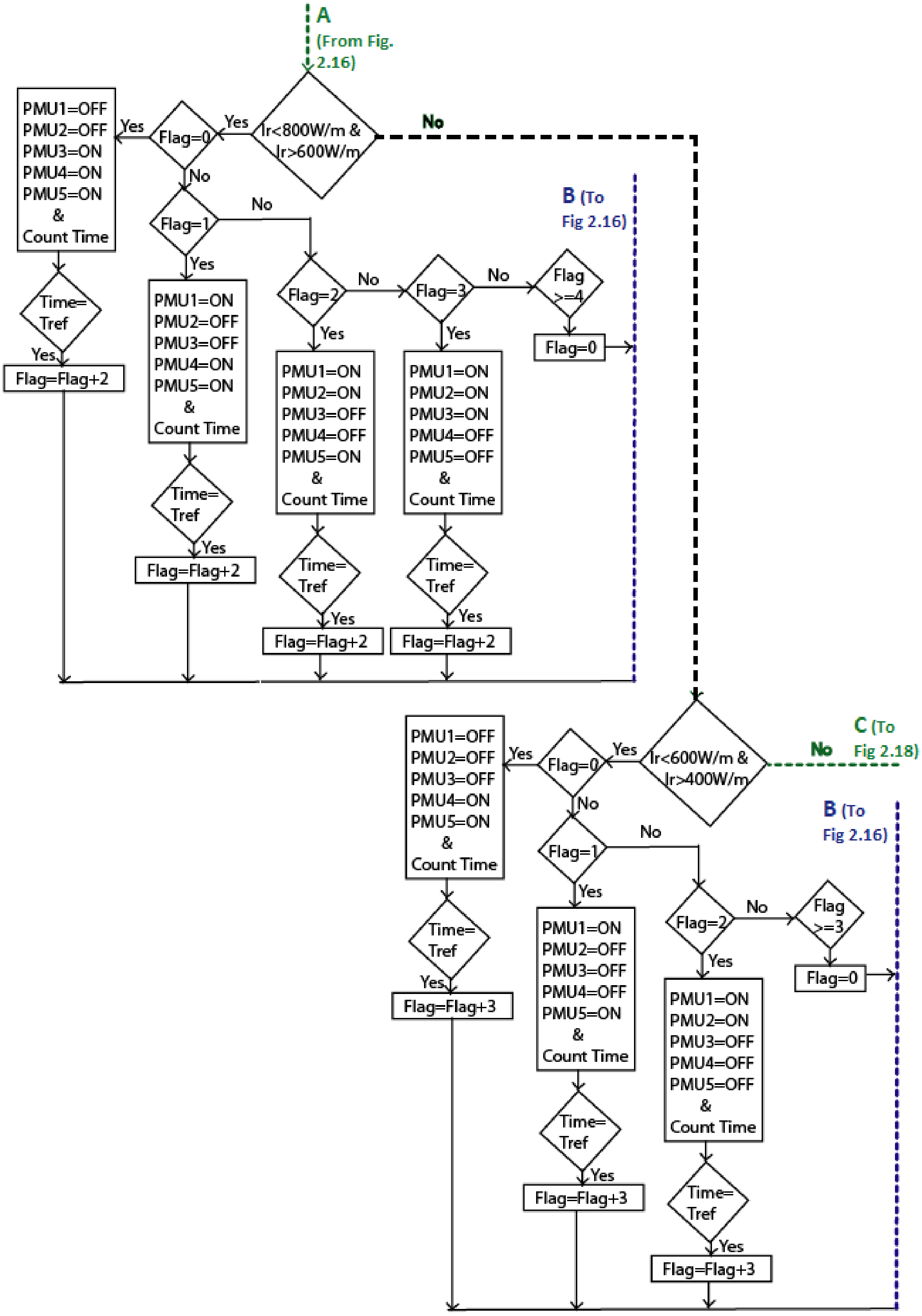

Fig. 2.25 Part 2 of Time Slot based Control Scheme for five PMUs in the dc microgrid architecture.

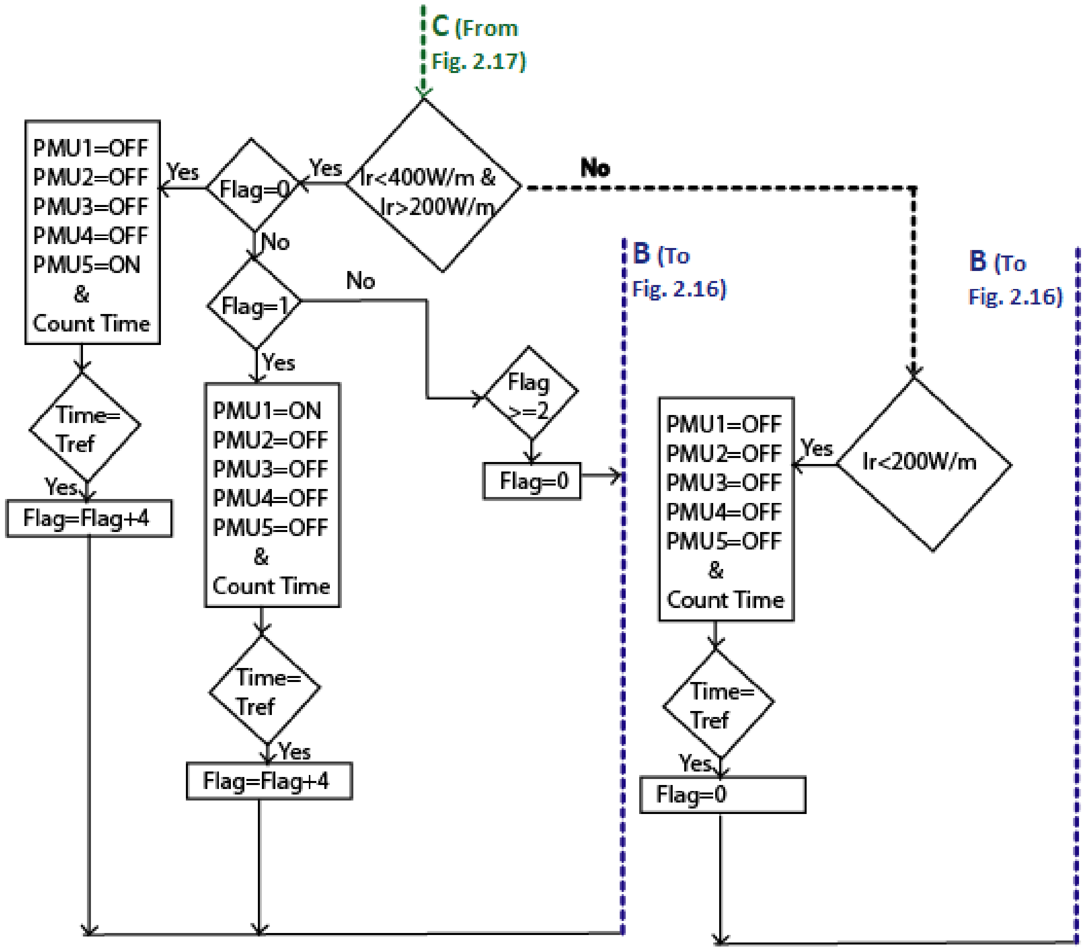

Fig. 2.26 Part 3 of Time Slot based Control algorithm for five PMUs in the dc microgrid architecture.

2.9.2 Control Scheme

When the irradiance is at the required level which is 1000W/m^2, power flows to the five PMUs as shown in Fig. 2.24. A Flag is defined to save the charging state of the PMUs and it is initial set to zero. When the irradiance falls down to 800W/m^2 and if the Flag is at zero, PMU1 is switched off keeping the other PMUs switched on and TC_1 starts counting the time. When TC_1 reaches the target time Tref (Tref is set based on the experiments) it adds 1 to Flag and check whether the irradiance condition has been changed. If the irradince level is still on 800W/m^2 and because the Flag is now at 1, then PMU2 is switched off keeping the other PMUs switched on and TC_2 starts counting the time. When TC_2 reaches the target time Tref it adds 1 to Flag and check whether the irradiance condition has been changed. So the process continues if the irradiance level is around to 800W/m^2 to the PMU5 and then the flag is reset to zero. The reset signal from the control interface resets all the

TCs at this time. When the irradiance falls down to 800W/m^2 and if the Flag is at one, PMU2 is switched off keeping the other PMUs switched on and TC_2 starts counting the time. So which PMU will be switched off at the start, depends on the value of the Flag.

When the irradiance falls down to 600W/m^2, PMU1 and PMU2 are switched off keeping the other PMUs switched on as shown in Fig. 2.25. TC_1 and TC_2 start counting the time. When TC_1 and TC_2 reach the target time Tref , it adds 2 to Flag and check whether the irradiance condition has been changed. If the irradince level is still on 600W/m^2, then PMU3 and PMU4 is switched off keeping the other PMUs switched on. TC_3 and TC_4 start counting the time. When TC_3 and TC_4 reach the target time Tref it adds 2 to Flag and check whether the irradiance condition has been changed. In this case only PMU5 is left and therefore, the flag is reset to zero. The reset signal from the control interface resets all the TCs at this time. Again, when the irradiance falls down to 600W/m^2 and if the Flag is at one, PMU2 and PMU3 is switched off keeping the other PMUs switched on. Similarly the when the Irradiance falls down to 400W/m^2 and the Flag is zero, PMU1, PMU2 and PMU3 are switched off as shown but if the Flag is one, PMU2, PMU3 and PMU4 are switched off keepin the others as switched on.

The case for 200W/m^2 is that it switches off PMU1, PMU2, PMU3 and PMU4 if the flag is set to zero where as PMU2, PMU3, PMU4 and PMU5 are switched off if theflag is set to 1 as illustrated in Fig. 2.26. All the PMUs are switched off if there is no irradiation at all.

Chapter 3

Modeling of the DC Microgrid Architecture

This chapter is divided in three parts. First the model for DC Microgrid Architecture with two PMUs has been presented. Then the control interface for the two stage conversion at the load side is modeled. At last, the timeslot based control scheme is modeled.

3.1 DC Microgrid Architecture with two PMUs

Output current and power of SunPower SPR-315E-WHT-D Module at different irradiance level and different temperature is shown in Fig. 3.1 and 3.2. Fig 3.1 shows output current and power for 1000W/m^2, 800W/m^2, 600W/m^2, 400W/m^2 and 200W/m^2. The current and maximum power point decreases sharply with fall in irradiance level. Fig 3.2 shows output current and power for 10ºC, 17.5ºC, 25ºC, 32.5ºC and 40ºC. The magnitude of the current remains almost the same but the maximum power point changes a little due to the shift slopes of the current. The DC microgrid structure with two PMUs is simulated using MATLAB Simulink as shown in Fig. 3.3. SunPower SPR-315E-WHT-D Module which follows NREL (National Renewable Energy Laboratory) System Advisor Model (Jan. 2014), is used as the PV module which takes two inputs of Sun irradiance and Cell temperature. Inside the source converter block, a MPPT Control and a Boost average converter are employed to achieve the maximum power point as well as boosting the voltage before transmission as shown in Fig. 3.4. The MPPT control uses Perturb and Observation(PO) algorithm which takes instantaneous voltage and current of the solar module as the input. There is an enable pin in the MPPT block which is switched to 1 to allow the continuous operation of the algorithm. Four other control parameters for PO algorithm are Initial value for D_b output (D_{binit}), Upper limit for D_b (D_{bmax}), Lower limit for D_b (D_{bmin}), Increment value used to increase/decrease (ΔD_b) where D_b is the Boost converter duty cycle. The boost converter uses the output duty cycle of the PO and generates the desired voltage realizing (2) and (3). A constant of $1e^{-6}$ is used to avoid the divide by zero condition in (3).

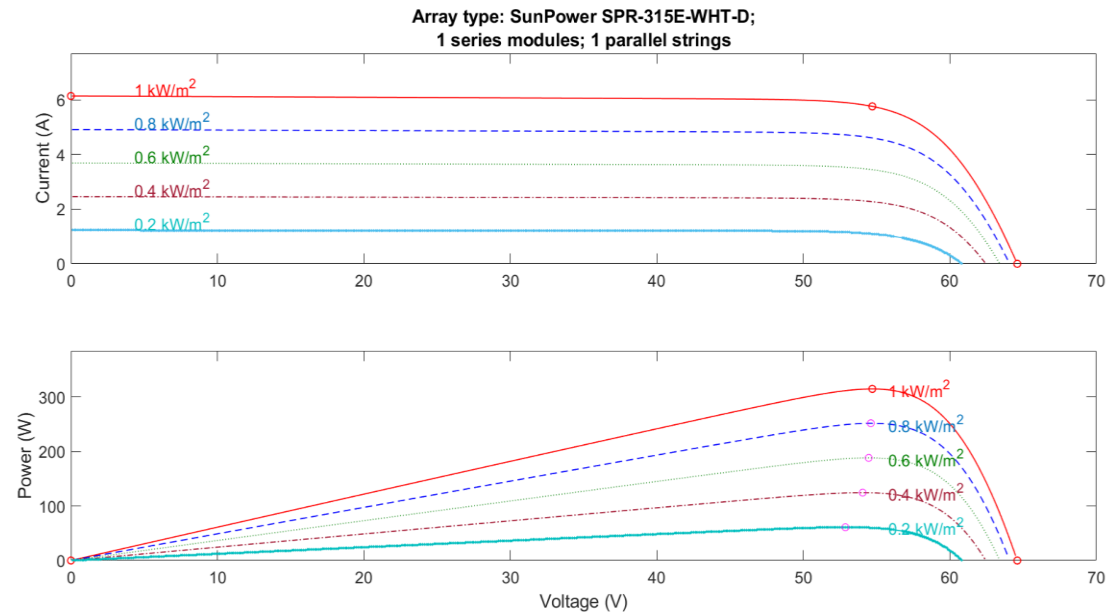

Fig. 3.1 Output Current and Power of SunPower SPR-315E-WHT-D Module at different irradiance level

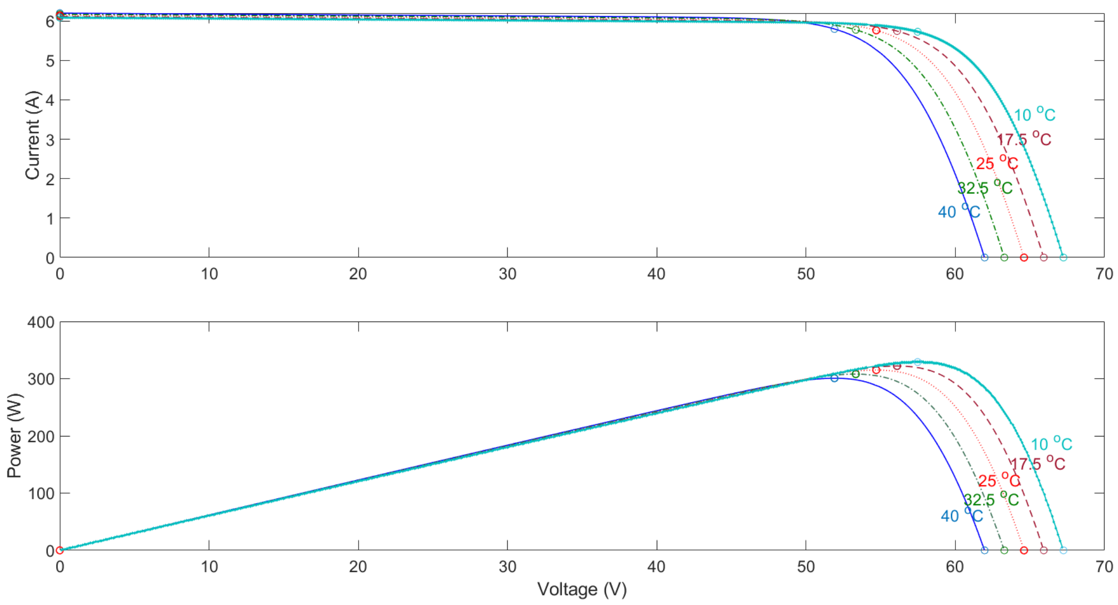

Fig. 3.2 Output Current and Power of SunPower SPR-315E-WHT-D Module at different temperature

The Boost Converter Average Model is shown in Fig. 3.5 while PMU circuit structure is shown in Fig. 3.6. Inside the PMUs, the value of leakage inductance L_{lk}, outer inductance L_{out} and the outer capacitance is 26µH, 10µH and 7500µF. The nominal power of the linear transformer is set to 150 VA in case of equal loads and frequency is adjusted according to the switching frequency of the active switches. The MOSFETs' on-resistance R_{on} and diode resistance R_D has the value 0.1Ω and 0.01Ω respectively. Lead acid battery is used with

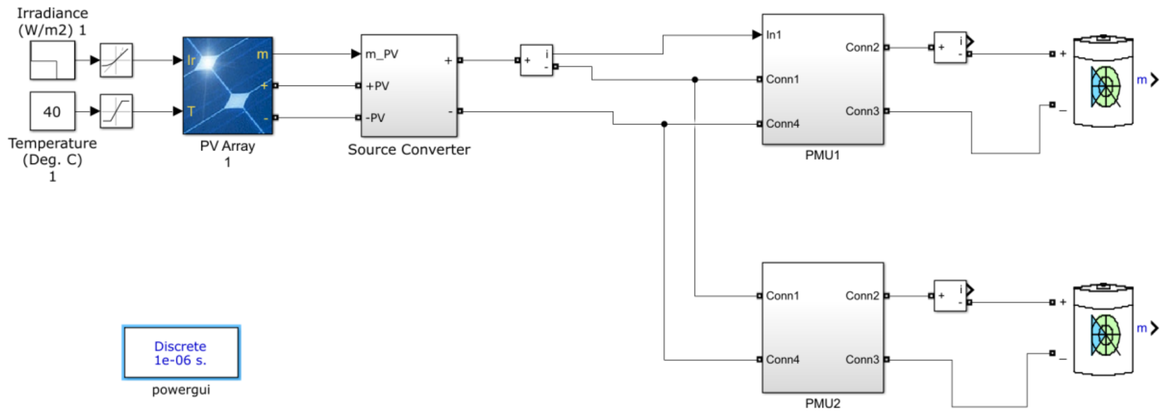

Fig. 3.3 DC microgrid architecture in MATLAB/ Simulink with two PMUs

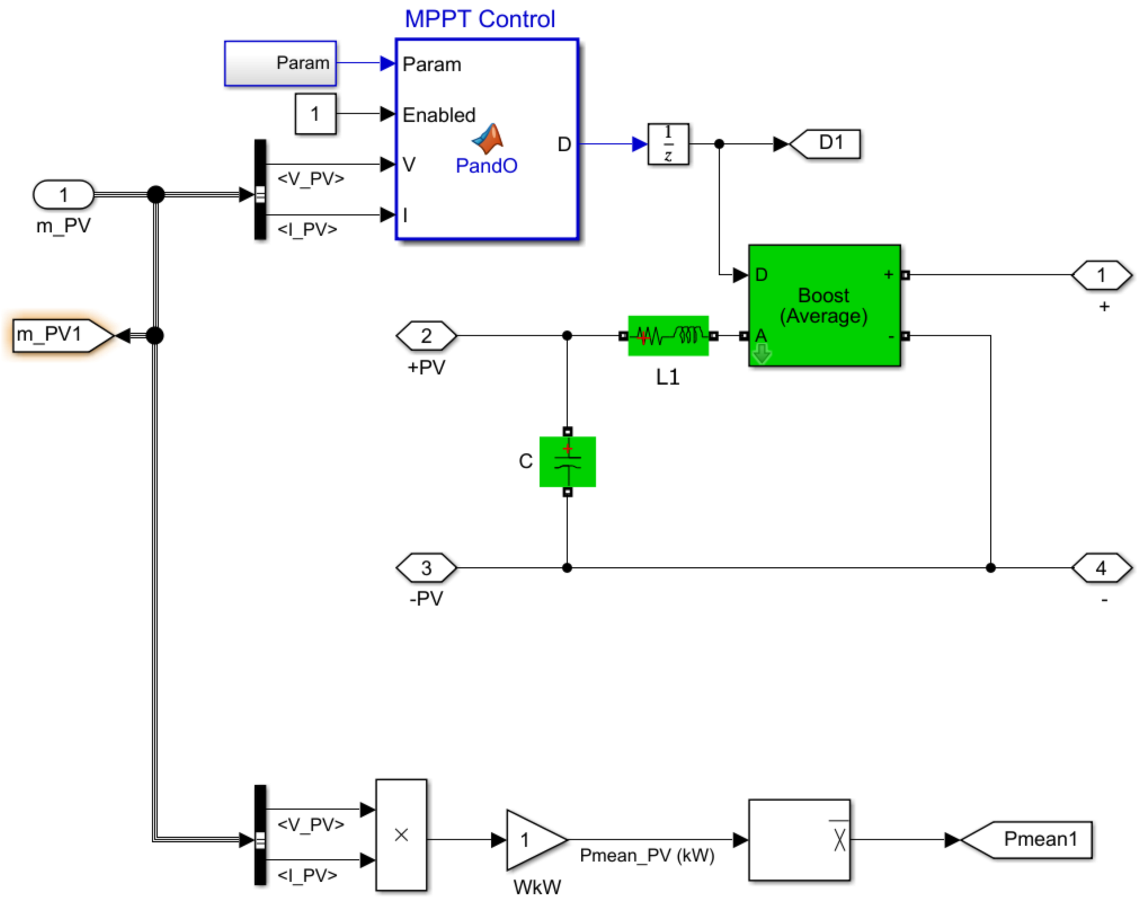

Fig. 3.4 Load Converter consisting of MPPT Control and Boost Converter in MATLAB/ Simulink

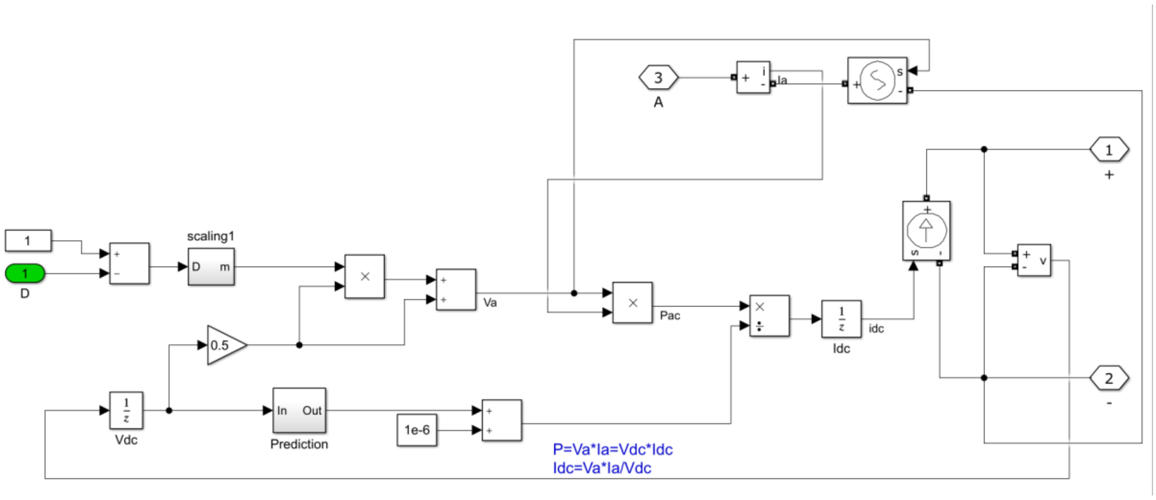

Fig. 3.5 Boost Converter Average Model in MATLAB/ Simulink

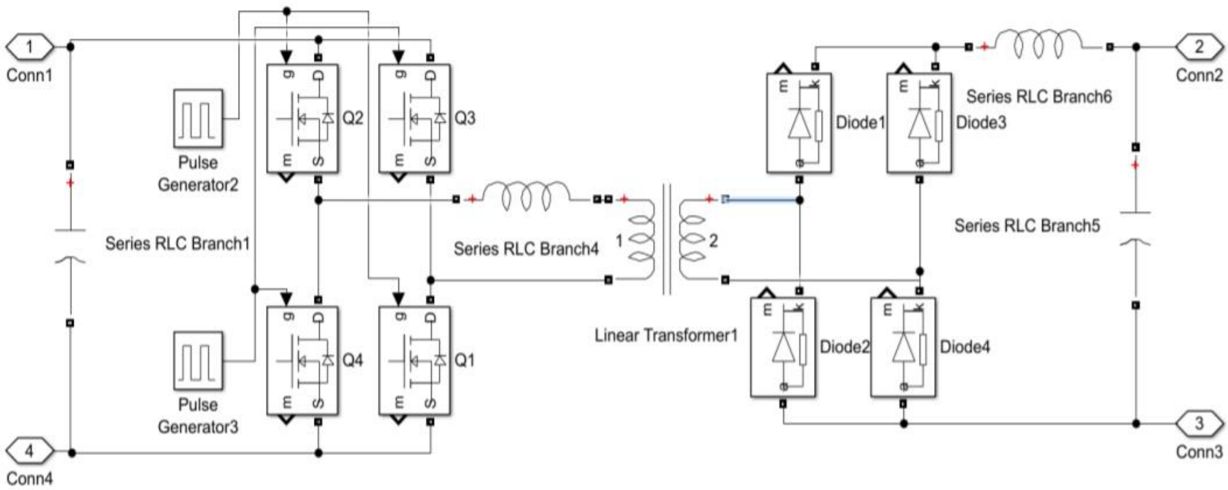

Fig. 3.6 PMU circuit structure in MATLAB/ Simulink

nominal voltage of 12V, rated capacity 120Ah, initial state of charge 75% and battery response time is 50min. The irradiation was varied from 1000W/m^2 to 500W/m^2, 500W/m^2 to 50W/m^2 and then back to 1000W/m^2 from 50W/m^2 for 12V and 36V batteries with same and different battery capacity in two different switching frequencies of 50kHz and 100kHz. The rated capacity was changed to 150Ah as needed. For 36V battery, initial state of charge is 75% and battery response time is 50min.The battery discharge characteristics for 12V and 36V batteries are shown Fig 3.7 and Fig. 3.8 generated using MATLAB\Simulink.

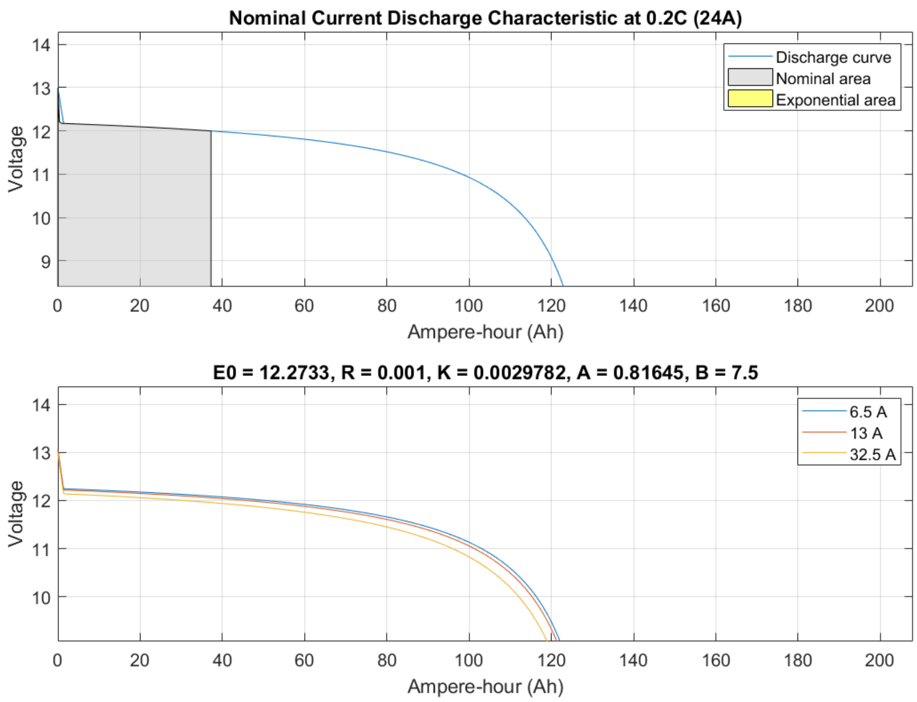

Fig 3.7 Battery Discharge Characteristics for 12V Battery

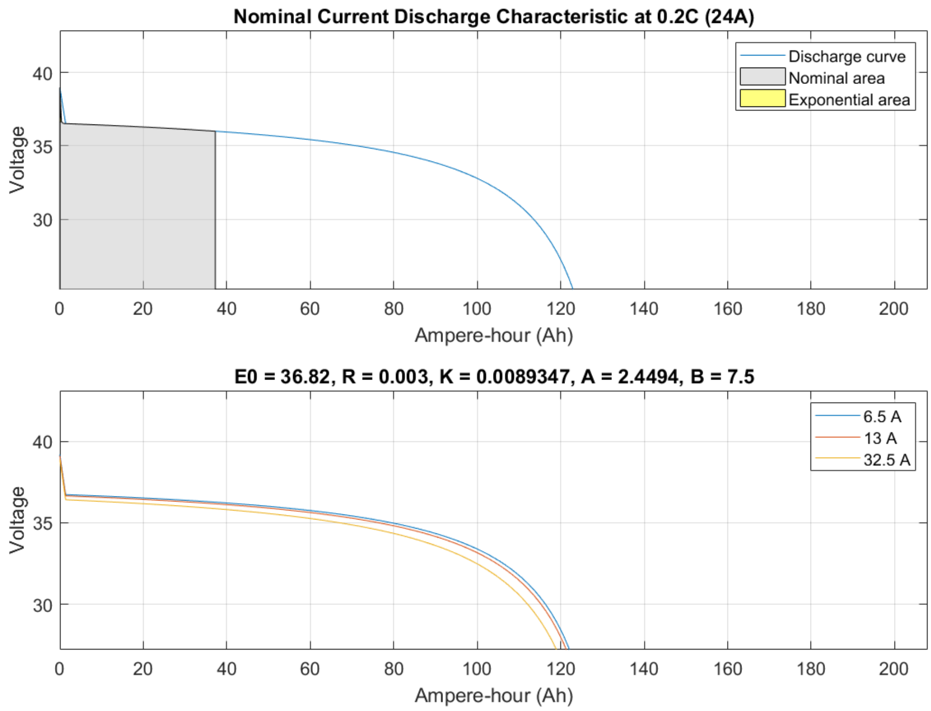

Fig 3.8 Battery Discharge Characteristics for 36V Battery

3.2 Control Interface for DC Microgrid Architecture with five identical PMUs

Simulation Model of DC Microgrid Architecture with Control Interface for five identical PMUs with 12V batteries and 250kHz switching frequency is depicted in Fig. 3.9. 100kHz switching frequency is used in the active switches of the Fanout Node.

The connection diagram of the Full Bridge Converter working as the Fanout node is depicted in Fig. 3.10. In the fanout node, the value of leakage inductance L_{lk}, outer inductance L_{out}, the input capacitance C_{in} and the outer capacitance C_{out} is 26µH, 10µH, 330µF and 0.154µF. The nominal power of the linear transformer is set to 300 VA in case of equal loads and frequency is adjusted according to the switching frequency of the active switches. The MOSFETs' on-resistance R_{on} and diode resistance R_D have the values of 0.1Ω and 0.01Ω respectively.

The circuit diagram of the buck converter working as the PMU is illustrated in Fig. 3.11. Inside the PMU, the value of inductance L, the input capacitance C_{in} and the outer capacitance C_{out} are 45µH, 20µF and 20µF respectively. The IGBT on-resistance has the value 0.1Ω. Lead acid battery is used with nominal voltage of 12V, rated capacity 120Ah, initial state of charge 75% and battery response time is 50min. There are five PMU block each connected in parallel to the Fanout node with Conn-1 and Conn-2 pin. The Out1 pin of the PMU1, PMU2, PMU3, PMU4 and PMU5 block represent the average power of block which is summed in the next function block

The control interface block takes irradiance as the input and generates five control signal Y1, Y2, Y3, Y4 and Y5 which is connected to the PMU1, PMU2, PMU3, PMU4 and PMU5 respectively.

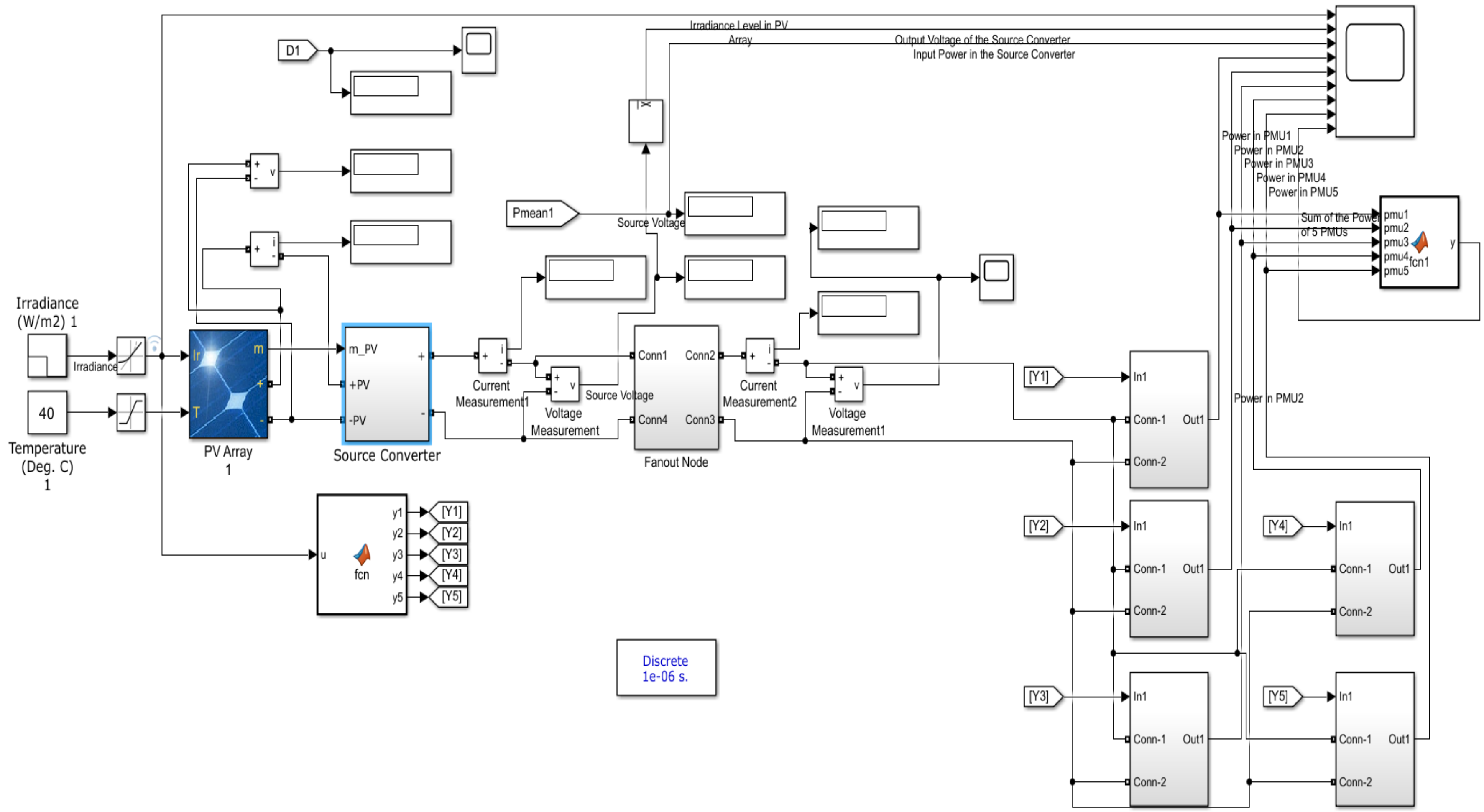

Fig. 3.9 Simulation Model of DC Microgrid Architecture with Control Interface for five identical PMUs with 12V batteries and 250kHz switching frequency while 100kHz switching frequency is used in the active switches of the Fanout Node in MATLAB/Simulink

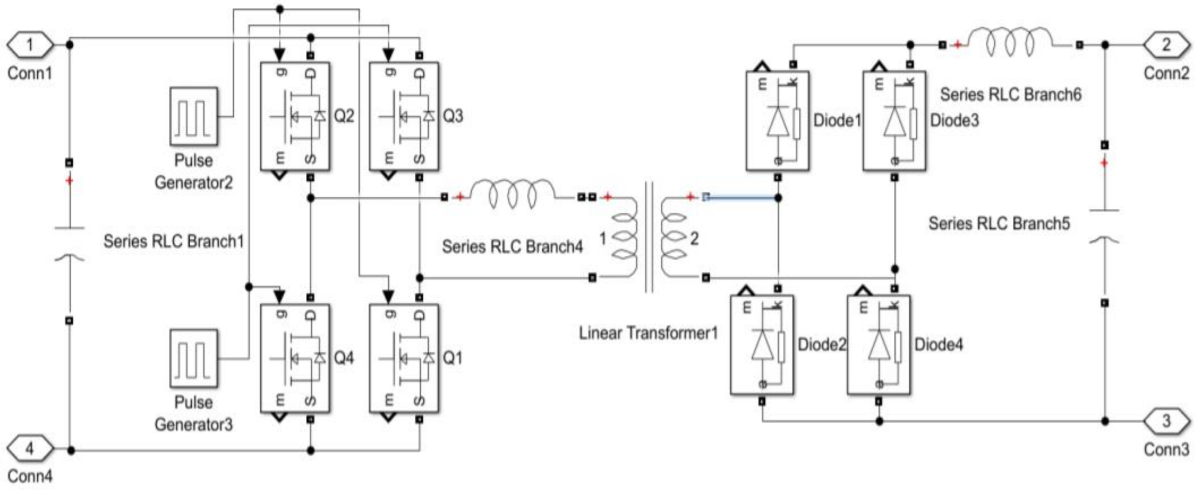

Fig. 3.10 Full Bridge Converter acting as Fanout node for Two Stage Conversion at the Load Side in DC microgrid architecture in MATLAB/Simulink

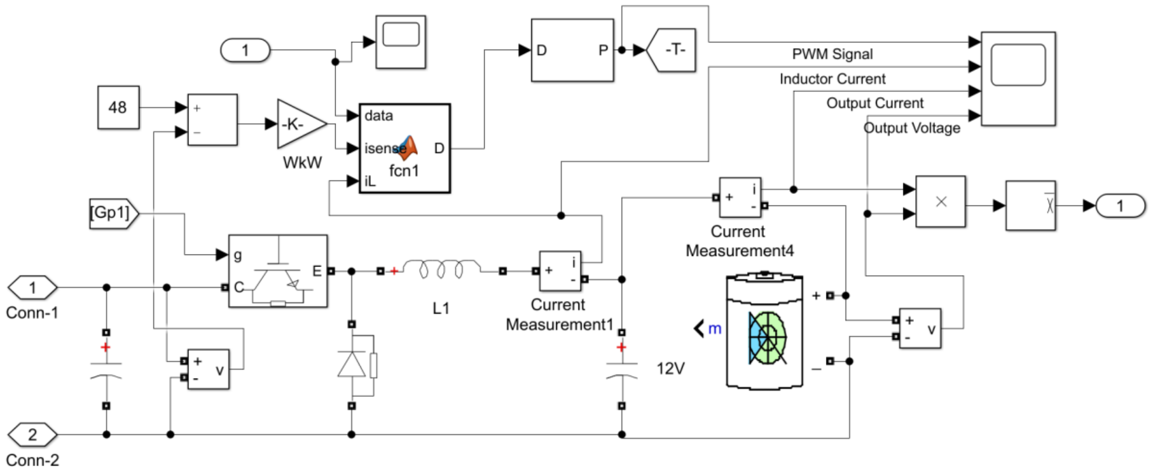

Fig. 3.11 Buck Converter acting as Fanout node for Two Stage Conversion at the Load Side in DC microgrid architecture in MATLAB/Simulink

3.3 Time Slot Based Control Scheme for DC Microgrid Architecture with five identical PMUs

Simulation Model of DC Microgrid Architecture with Modified Control Interface with Time Slot based Control Scheme is shown in Fig. 3.12. Five identical PMUs with 12V batteries and 250kHz switching frequency while 100kHz switching frequency is used in the active switches of the Fanout Node in MATLAB/Simulink The settings of the Fanout

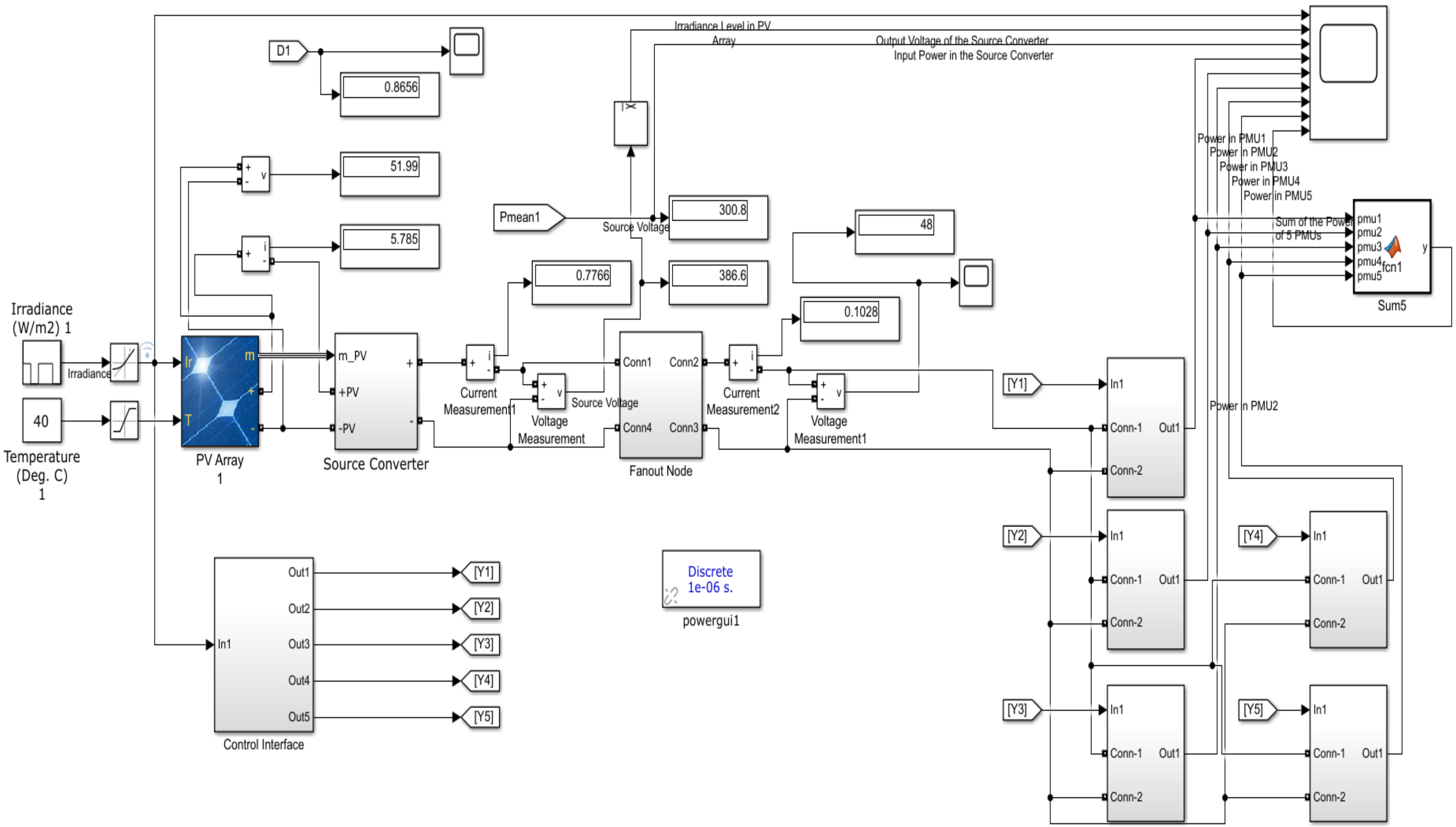

Fig. 3.12 Simulation Model of DC Microgrid Architecture with Modified Control Interface with Time Slot based Control Scheme for five identical PMUs with 12V batteries and 250kHz switching frequency while 100kHz switching frequency is used in the active switches of the Fanout Node in MATLAB/Simulink

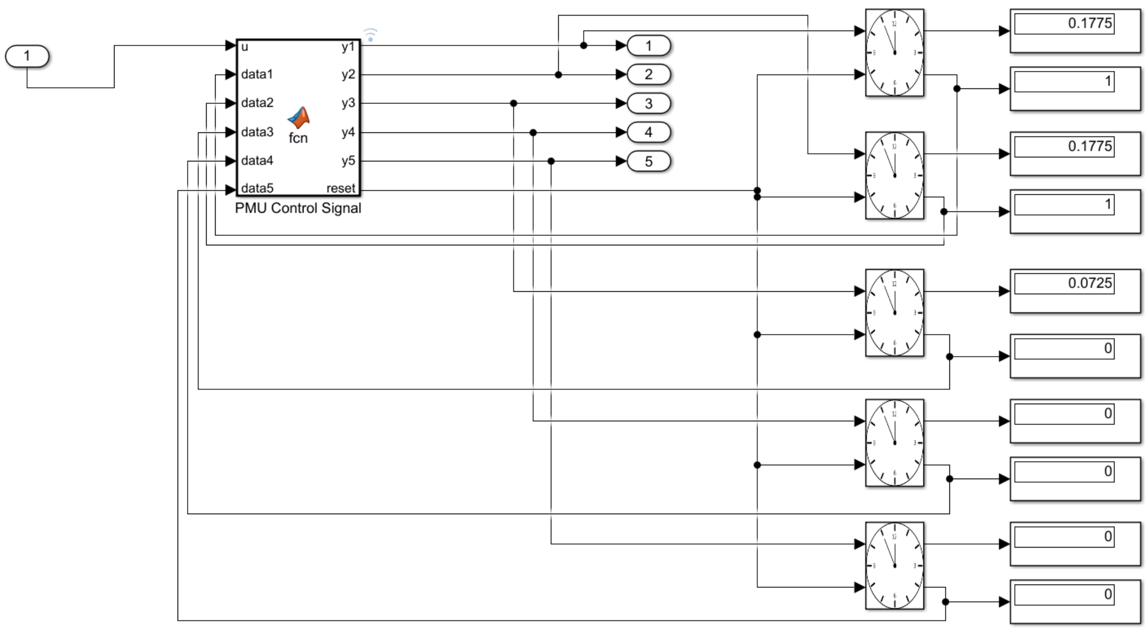

Fig. 3.13 Control Interface Block where 5 timer counter is used for Time Slot Based Control Algorithm in MATLAB/Simulink

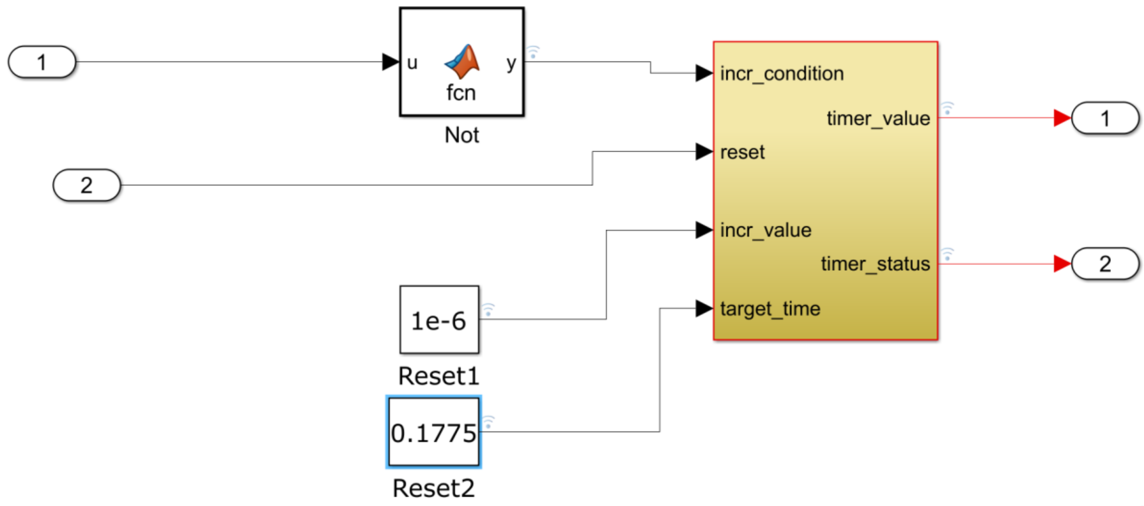

Fig. 3.14 Timer counter Block which is used for Time Slot Based Control Algorithm in MATLAB/Simulink

node and PMUs are kept similar as in 4.2. In the Fanout node Phase Shifting technique has been included [94]. The Control Interface block now consists of PMU Control Signal Block and Five Timer Counter(TC) Block. In Control Interface Block, TC is used for the Time Slot based Control Scheme in DC Microgird Architecture as shown in Fig. 3.13. Five TCs are connected with the control signal of the five PMUs. The five control signal is connected with increment conditions (ICs) of the five TCs. Each TC has a timer status (TS) which is send as the feedback to the control interface. The reset signal from the PMU control signal block is connected to the reset (R) of each TCs.

Timer counter Block used for the Time Slot Based Control Scheme is shown in Fig. 3.14. A logical not function is used to IC to adjust the PMU control signal. The increment value is set to 1e-6 which is equal to the sampling frequency. The target time Tref in the timer counter was set to 0.1775s for the simulation time of 2s.

Chapter 4

Results and Discussion

The result and discussion chapter is divided in three parts. First the results for DC Microgrid Architecture with two PMUs has been presented. Then the analysis of the control interface for the two stage conversion at the load side is depicted. At last, the simulation results for the timeslot based control scheme is presented.

4.1 DC Microgrid Architecture with two PMUs

Fig. 4.1 shows the simulation results for 12V batteries with same and different capacity in two separate PMUs in 50kHz switching frequency for the active switches. The output voltage of the source converter tends to show minor change due to fluctuation of the irradiance which is very encouraging. The average power is divided into PMUs equally when the battery parameters are uniform. The battery with higher rated capacity draws higher power resulting in unequal power sharing between the two PMUs although the source converter output voltage is almost the same as the former case. The average power from the PV array and the sum of the average power of the PMUs are very closely matched in both cases and proportionate to the irradiance pattern. Fig. 4.2 shows the simulation results for 36V batteries with same and different capacity in two separate PMUs in 50kHz switching frequency for the active switches. The results are similar compared to the case of 12V batteries. An interesting observation is green dotted line are much closer to the blue solid when different battery capacity has been used.

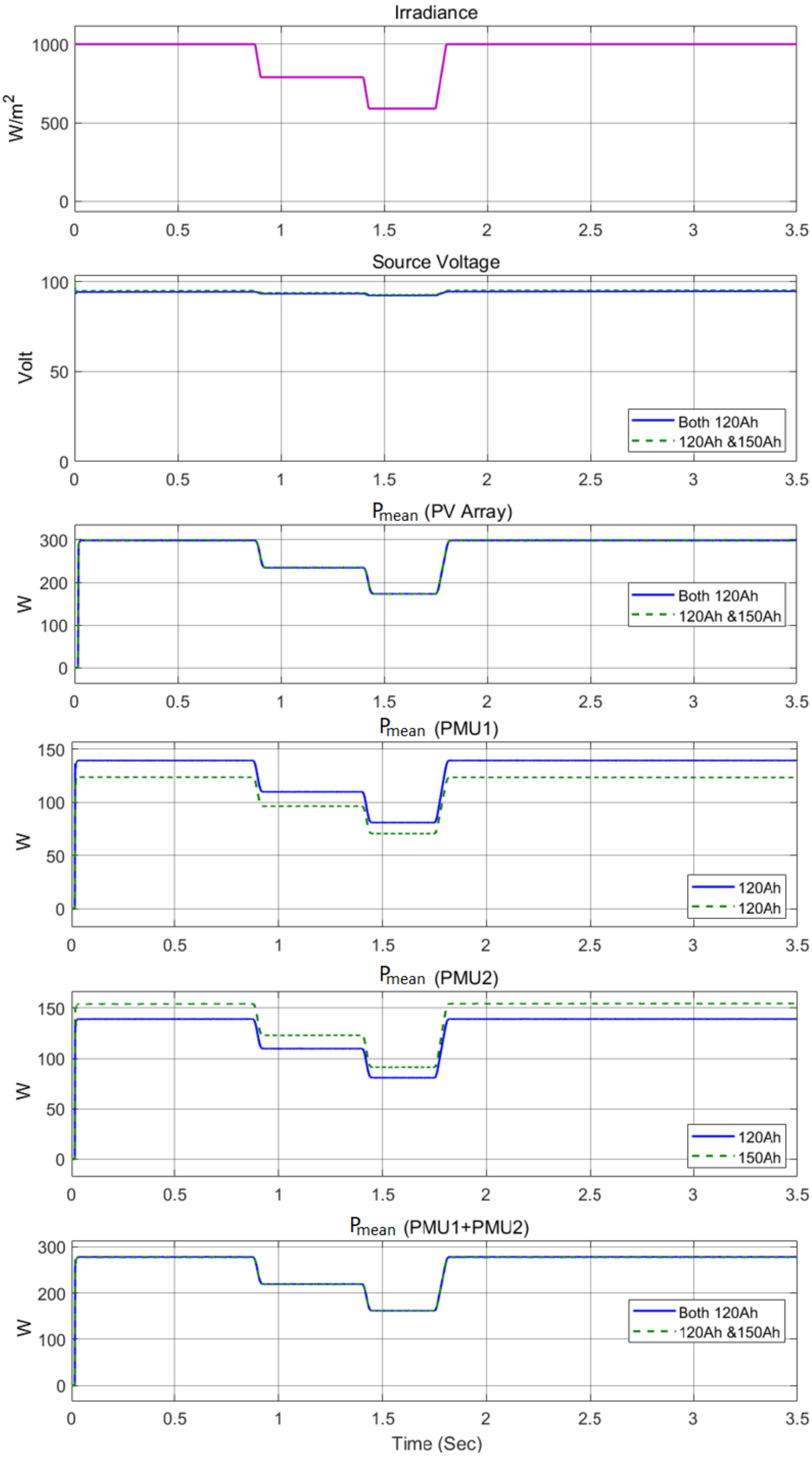

Fig. 4.1 Simulation results for 12V batteries with same and different capacity in two separate PMUs in 50kHz switching frequency for the active switches. The irradiance pattern was kept identical for each case. The blue solid line represents the case when the two separate PMUs have same battery capacity while the green dotted line depicts the case with two different battery capacity in two separate PMUs.

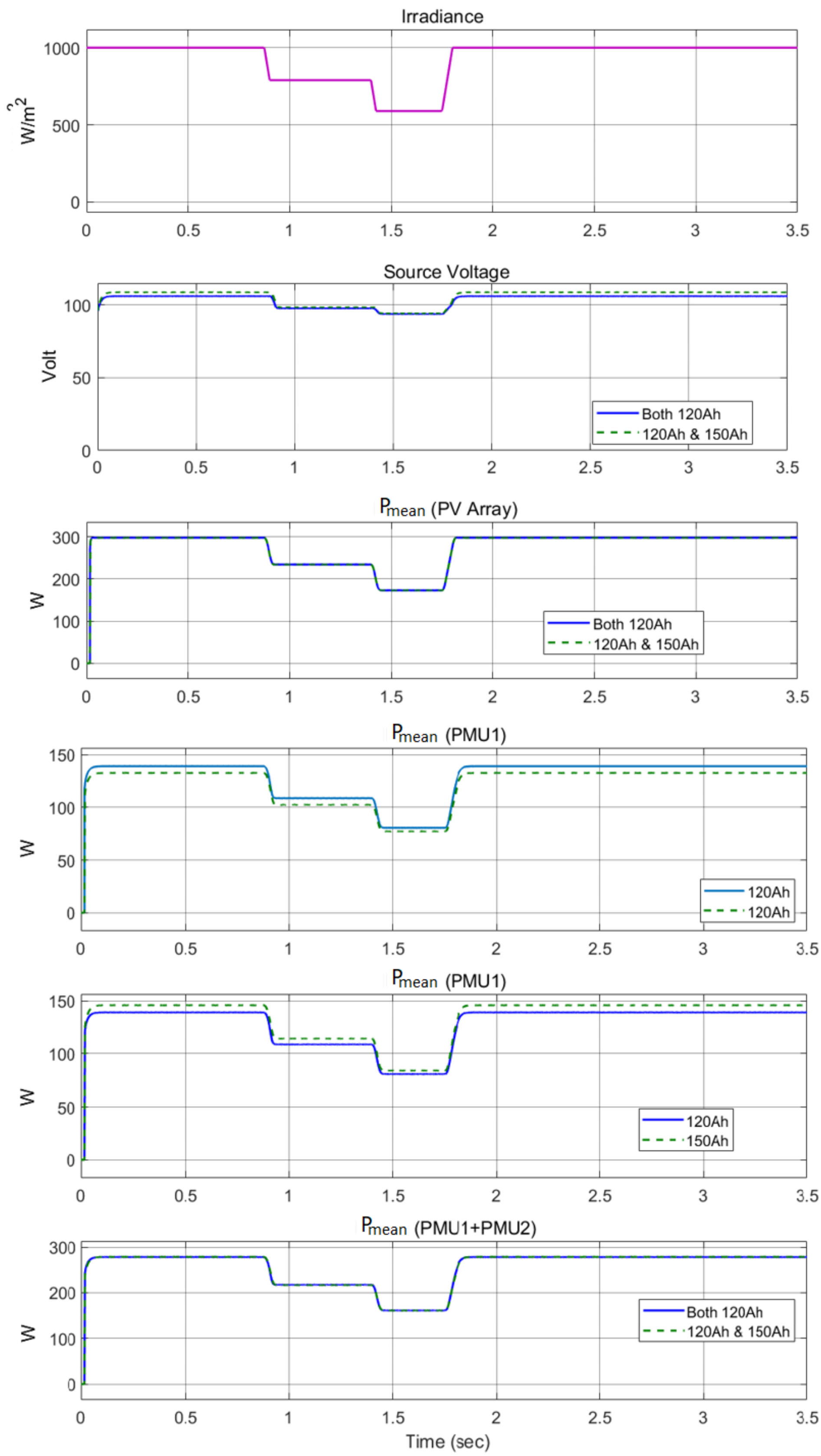

Fig. 4.2 Simulation results for 36V batteries with same and different capacity in two separate PMUs in 50kHz switching frequency for the active switches. The irradiance pattern was kept identical for each case. The blue solid line represents the case when the two separate PMUs have same battery capacity while the green dotted line depicts the case with two different battery capacity in two separate PMUs.

TABLE 4.1 (a)

Performance Analysis of PV Array, Source Converter in the Microgrid Architecture with two PMUs for Different Switching Frequencies and Battery Ratings

Switching Frequency	Battery	PV Array		Source Converter			MPPT Duty Cycle
		V (Volt)	I (Ampere)	V (Volt)	I (Ampere)	Power (Watt)	
50 kHz	12V 120Ah	51.84	5.76	94.22	3.173	298.3	0.4392
	12V 120Ah 12V 150Ah	52.06	5.73	94.84	3.132	298.2	0.4717
	36V 120Ah	51.68	5.76	106.1	2.812	297.5	0.4905
	36V 120Ah 36V 150Ah	51.88	5.73	108.8	2.725	297.1	0.5235
100 kHz	I2V 120Ah	51.76	5.77	93.26	3.208	298.5	0.4246
	12V 120Ah 12V 150Ah	51.82	5.76	94.59	3.151	298.1	0.4479
	36V 120Ah	51.68	5.76	112.6	2.647	297.1	0.5211
	36V 120Ah 36V 150Ah	51.99	5.72	113.5	2.614	296.8	0.5486

TABLE 4.1 (b)

Performance Analysis of PMUs in the Microgrid Architecture with two PMUs for Different Switching Frequencies and Battery Ratings

Switching Frequency	Battery	PMU1			PMU2			Efficiency (Percent)
		V (V)	I (A)	P (W)	V (V)	I (A)	P (W)	
50 kHz	12V 120Ah	12.17	11.68	139	12.17	11.68	139	93.19
	12V 120Ah 12V 150Ah	12.17	10.14	123.5	12.17	12.84	154	93.06
	36V 120Ah	36.48	3.71	139.1	36.48	3.71	139.1	93.51
	36V 120Ah 36V 150Ah	36.47	3.53	132.8	36.47	3.855	146	93.84
100 kHz	12V 120Ah	12.17	11.62	139.2	12.17	11.62	139.2	93.27
	12V 120Ah 12V 150Ah	12.16	10.79	132	12.17	11.88	145.3	93.02
	36V 120Ah	36.48	3.85	139.6	36.48	3.85	139.6	93.98
	36V 120Ah 36V 150Ah	36.48	3.4	124.3	36.48	4.2	153.9	93.73

Table I shows the simulation results for two different battery voltage in two disparate switching frequency. For 36V batteries the transformer ratings were adjusted to maintain the output of the PMUs to the desired level. The MPPT duty cycle moved to a different point resulting in a slightly different source converter output voltage around 110V but keeps average power around 297W. The efficiency estimated in all different cases is more than 93% which ensures the stability of the system in different battery voltage level and frequency. [92]

4.2 Control Interface for DC Microgrid Architecture with five identical PMUs

The irradiation has been varied from 1000W/m^2 to 799W/m^2, 799W/m^2 to 599W/m^2 and then back to 1000W/m^2 from 699W/m^2 for 12V batteries with the same capacity with switching frequencies of 100kHz for the fanout node and 250kHz for the buck converters in the PMUs. Fig. 4.3 shows the simulation results for five identical PMUs. (a) shows the irradiation pattern, (b) output voltage of the source converter, (c) input power of the source converter, (d)-(h) power consumed by PMU1 to PMU5 and (i) sum of the power of 5 PMUs. PMU1 and PMU2 is shut down sequentially with the fall of irradiance level.

The output voltage of the source converter tends to show minor change due to fluctuation of the irradiance. The average power is divided into PMUs equally when there is sufficient irradiance of 1000W/m^2. When the irradiance falls down to 799W/m^2, the control block sends a signal to put off the PMU1 and it continues to supply power to the other PMUs. Similarly, when the irradiance gets down to 599W/m^2, the control blocks shuts down PMU2. When the irradiance level gets back to 1000W/m^2, PMU1 draws more power than the other 4 PMUs and PMU2 draws more power than the three PMUs which are always connected throughout the process. The average power from the PV array and the sum of the average power of the PMUs are very closely matched in both cases and proportionate to the irradiance pattern. Fig. 4.4 shows input current, output current and output voltage of the Fanout Node. Fig. 4.5 depicts the PWM signal, output current and output voltage of the PMU1 and PMU2.

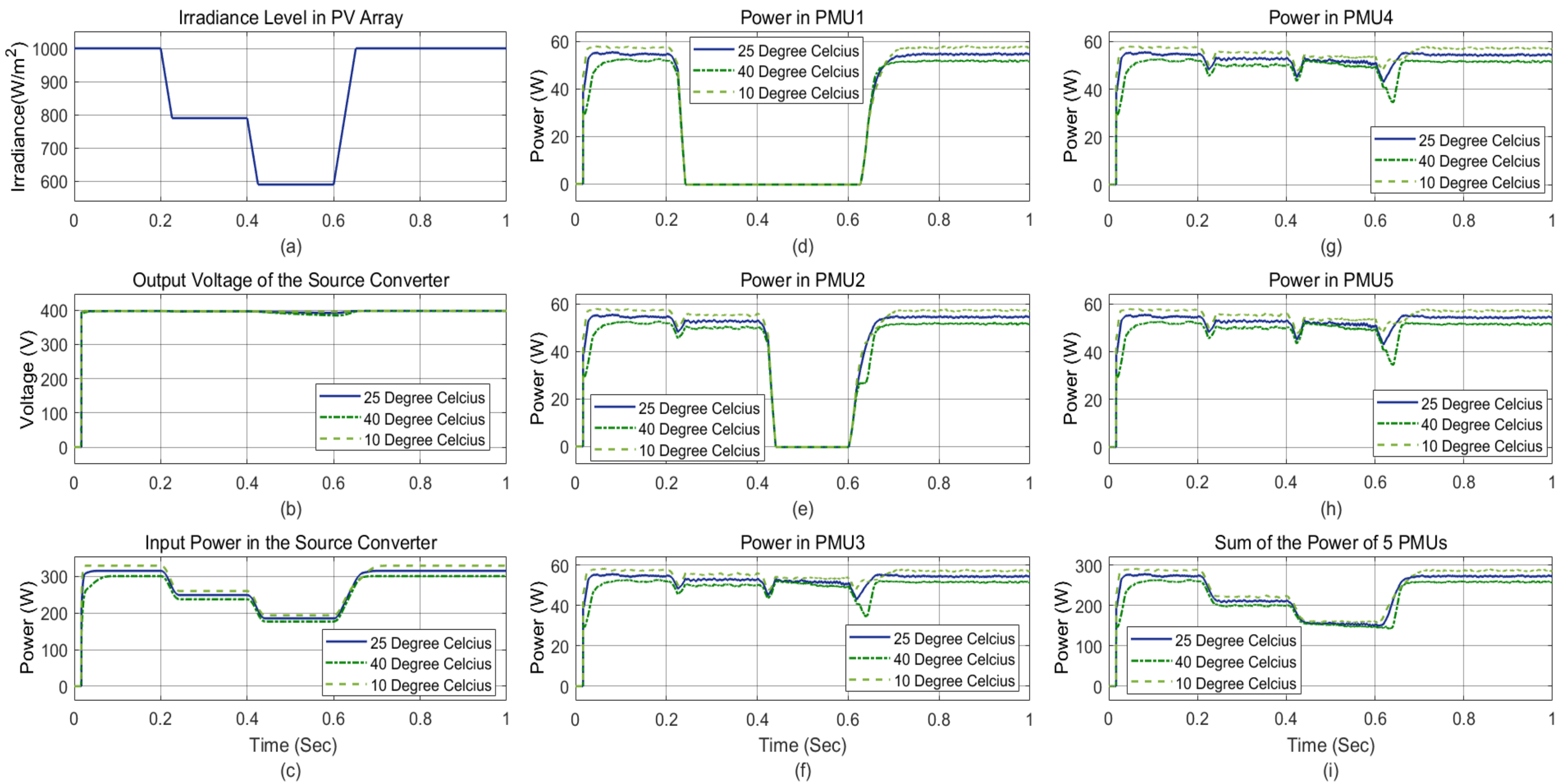

Fig. 4.3 Simulation results for five identical PMUs with 12V batteries and 250kHz switching frequency while 100kHz switching frequency is used in the active switches of the Fanout Node for one second time period at three different temperatures (10, 25 and 40 Degree Celsius). (a) shows the irradiation pattern, (b) output voltage of the source converter, (c) input power of the source converter, (d)-(h) power consumed by PMU1 to PMU5 and (i) sum of the power of 5 PMUs. PMU1 and PMU2 is shut down sequentially with the fall of irradiance level.

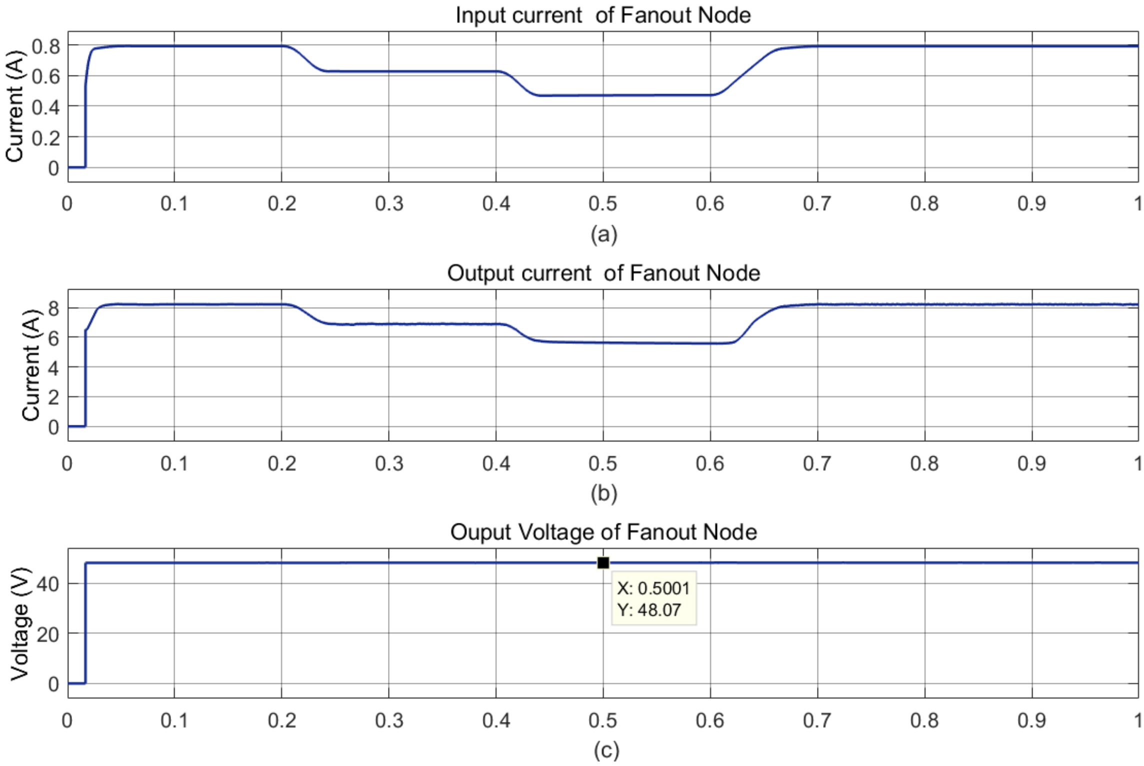

Fig. 4.4 (a) Input current, (b) output current and (c) output voltage of Fanout node at 25 Degree Celsius temperature.

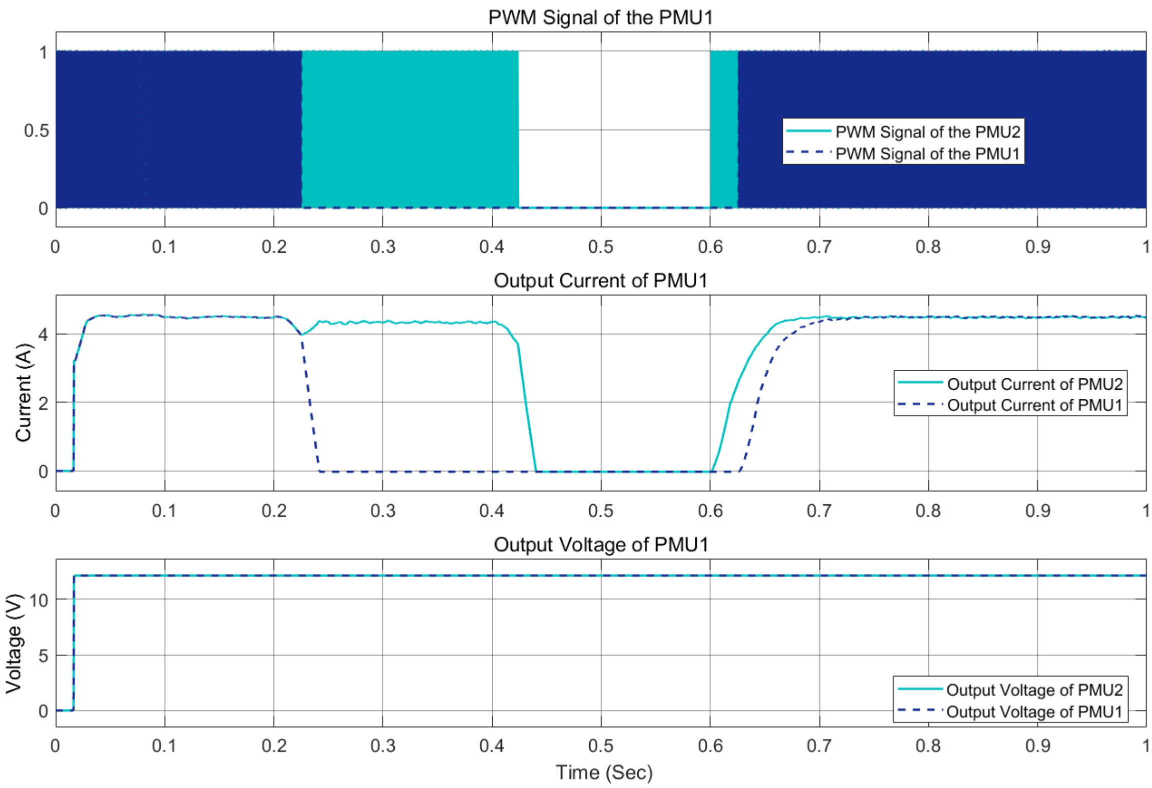

Fig. 4.5 (a) PWM signal, (b) output current and (c) output voltage of PMU1 and PMU2 at 25 Degree Celsius temperature.

Table II shows the simulation results for three different irradiance levels for 25 degree celsius. For 1000W/m^2, the source converter output voltage is 397V and average power is

315.1W. Five PMUs consume the equal amount of power 56.3W and the overall efficiency is found to be 89.3%. At 799W/m^2, the source converter output voltage is 395.9V and average power is 248.1W. PMU1 consumes 0W while the four other consumes 54.4W and the overall efficiency is found to be 87.5%. At 599W/m^2, the source converter output voltage goes down to 393.4V and average power is 185.2W. PMU1 and PMU2 consume 0W while the three other consumes 53.2W and the overall efficiency is found to be 85.9%. In all three cases the average power is exactly or very close to the MPPT power. The efficiency estimated in all different cases and similar result in different temperature (10 and 40 degree celsius) ensures the stability of the system in different irradiance levels. [95]

TABLE 4.2 (a)
Performance Analysis of PV Array, Source Converter and Fanout Node in the DC Microgrid Architecture for Different Irradiance Levels

Irradiance (W/m^2)	PV Array		Source Converter			MPPT Duty Ratio	Fanout Node Voltage
	V	I	V	I	Power W		
1000	54.69	5.76	397.0	0.79	315.1	0.8624	47.71
799	54.58	4.56	395.9	0.63	248.1	0.8622	47.99
599	54.34	3.41	393.4	0.47	185.2	0.8619	48..05

TABLE 4.2 (b)
Performance Analysis of the Five Identical PMUs for Different Irradiance Levels in the DC Microgrid Architecture

Irradiance (W/m^2)	PMU1 Power W	PMU2 Power W	PMU3 Power W	PMU4 Power W	PMU5 Power W	Efficiency of Fanout Node and PMU (%)
1000	56.3	56.3	56.3	56.3	56.3	89.3
799	0	54.4	54.4	54.4	54.4	87.5
599	0	0	53.2	53.2	53.2	85.9

4.3 Time Slot Based Control Scheme for DC Microgrid Architecture with five identical PMUs

Simulation results for Irradiation Pattern 1 of DC Microgrid Architecture with Modified Control Interface for Time Slot based Control Scheme is shown in Fig. 4.6. When the irradiance falls from 1000W/m^2 to 800W/m^2, at first PMU1 is switched off keeping the other PMUs switched on and TC_1 starts counting the time. When TC_1 reaches the target time Tref it adds 1 to Flag and check whether the irradiance condition has been changed. The irradince level is still on 800W/m^2 and because the Flag is now at 1, then PMU2 is switched off keeping the other PMUs switched on and TC_2 starts counting the time. When TC_2 reaches the target time Tref it adds 1 to Flag and check whether the irradiance condition has been changed. The process continues to the PMU5 and then the flag is reset to zero. The reset signal from the control interface resets all the TCs at this time. Here, the irradiance level is still on the 800W/m^2, so the PMU1 and then PMU2 again gets switched off sequentially for a brief period of time.

PWM signal, Inductor Current, Output current and Output voltage of PMU1 and PMU2 for Irradiation Pattern 1 are shown in Fig. 4.7 and Fig. 4.8 respectively. The inductor current becomes zero when PWM signal is turned to zero. The output current of the buck converter is zero indicates that the battery is not charging at this time. However, output voltage doesn't show any change because of the battery voltage.

Simulation results for Irradiation Pattern 2 of DC Microgrid Architecture with Modified Control Interface for Time Slot based Control Scheme is shown in Fig. 4.9. When the irradiance falls from 1000W/m^2 to 800W/m^2, at first PMU1 is switched off keeping the other PMUs switched on and TC_1 starts counting the time. When TC_1 reaches the target time Tref it adds 1 to Flag and check whether the irradiance condition has been changed. The irradince level falls from 800W/m^2 to 600W/m^2 and because the Flag is now at 1, then PMU2, PMU3 are switched off keeping the other PMUs switched on and TC_2 ,TC_3 starts counting the time. When TC_2 ,TC_3 reaches the target time Tref it adds 2 to Flag and check whether the irradiance condition has been changed. Now, the irradiance is changed from 600W/m^2 to 800W/m^2 and the Flag is now 3. Therefore PMU4 is switched off keeping the other PMUs switched on and TC_4 starts counting the time. When TC_4 reaches the target

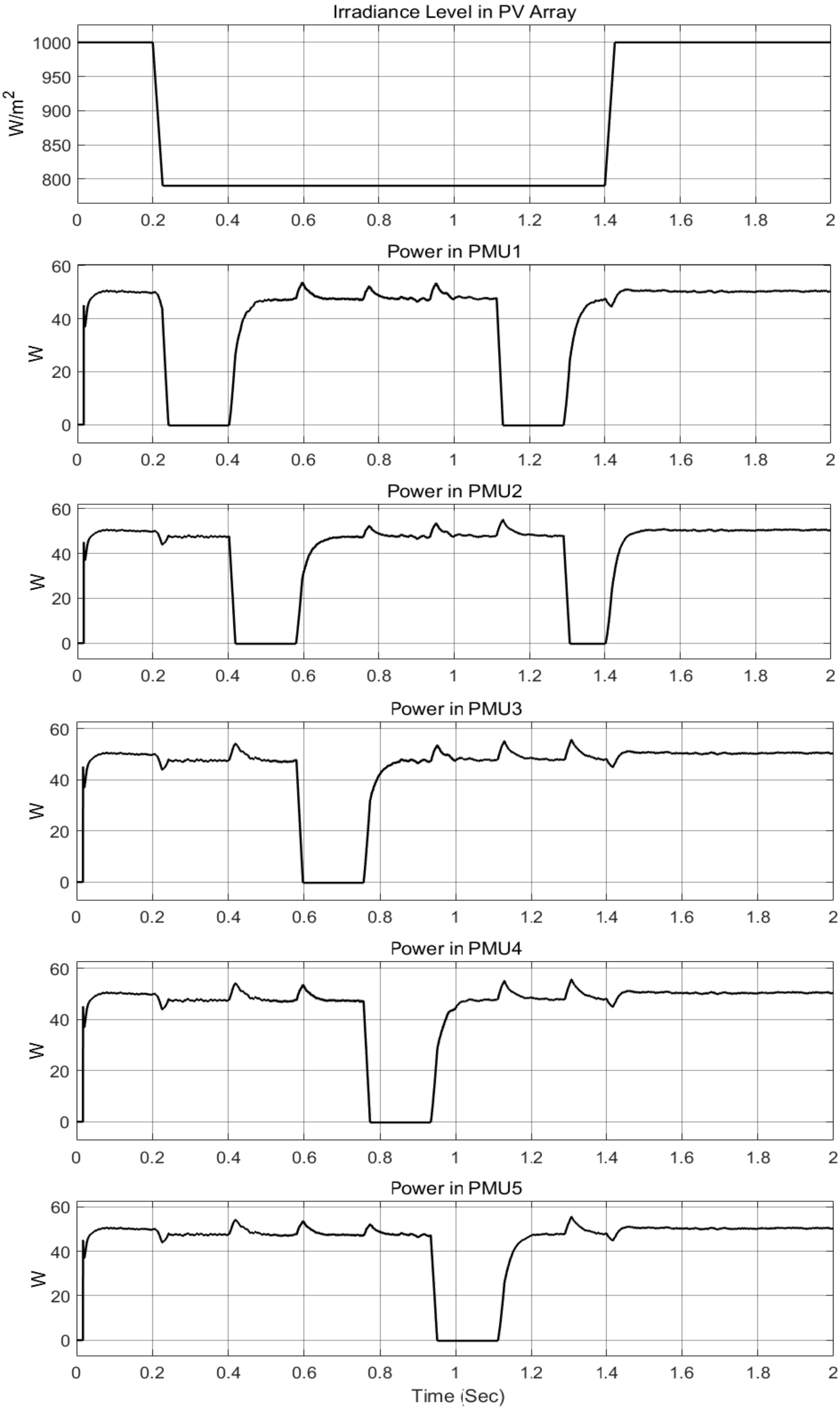

Fig. 4.6 Simulation results for five identical PMUs with 12V batteries and 250kHz switching frequency while 100kHz switching frequency is used in the active switches of the Fanout Node for Time Slot based Algorithm for Irradiation Pattern 1. PMUs are shut down sequentially with the fall of irradiance level.

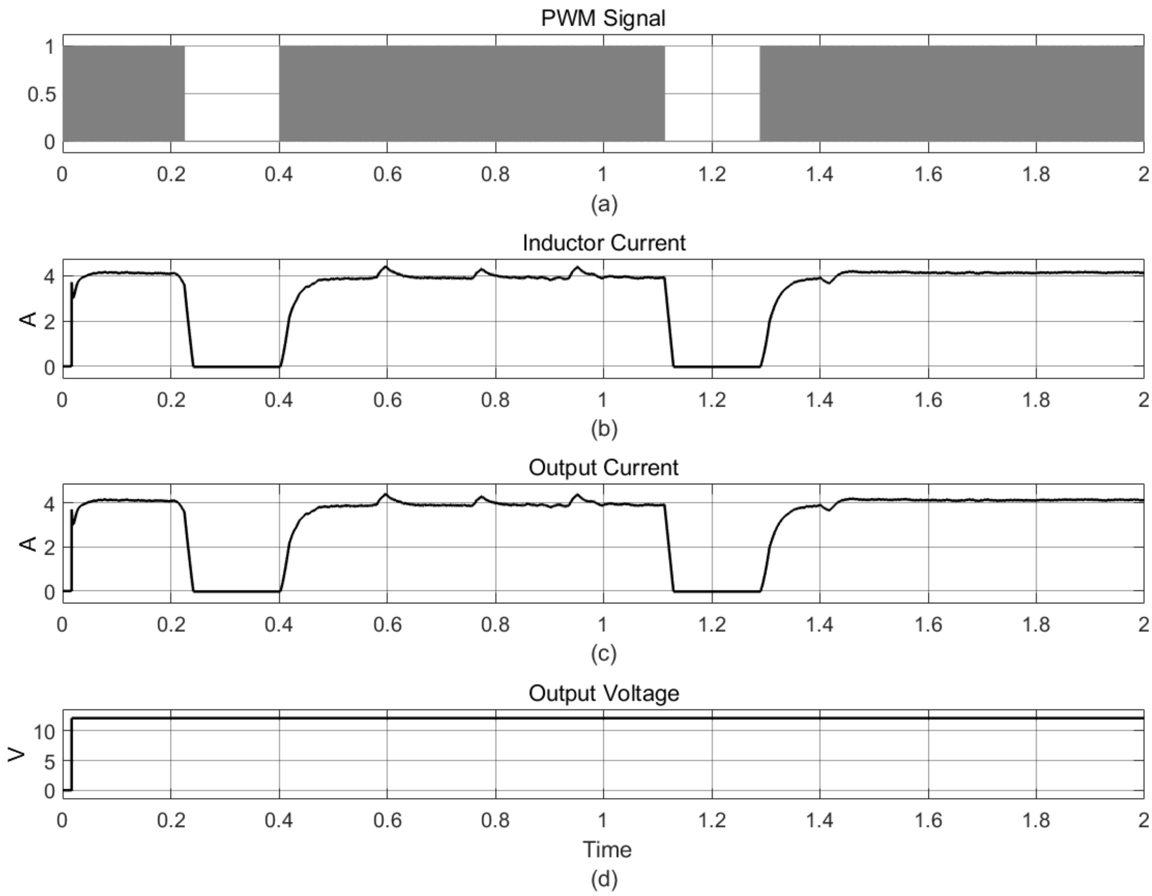

Fig. 4.7 (a) PWM signal, (b) Inductor Current, (c) Output current and (d) Output voltage of PMU1 for Irradiation Pattern 1.

time Tref it adds 1 to Flag and check whether the irradiance condition has been changed. The irradince level is still on 800W/m^2 and because the Flag is now at 4, then PMU5 is switched off keeping the other PMUs switched on and TC_5 starts counting the time. When TC_5 reaches the target time Tref it adds 1 to Flag and check whether the irradiance condition has been changed. Now because the Flag has become 5 it resets to zero and reset all the timer counter with it. The irradince level is still on 800W/m^2 and because the Flag is now at 0, then PMU1 is switched off keeping the other PMUs switched on and TC_1 starts counting the time. When TC_1 reaches the target time Tref it adds 1 to Flag and check whether the irradiance condition has been changed. The irradince level is still on 800W/m^2 and because the Flag is now at 1, then PMU2 is switched off keeping the other PMUs switched on and TC_2 starts counting the time. Now the irradiance level drops at 600W/m^2 and because the Flag is now at 1, then PMU2, PMU3 are switched off keeping the other

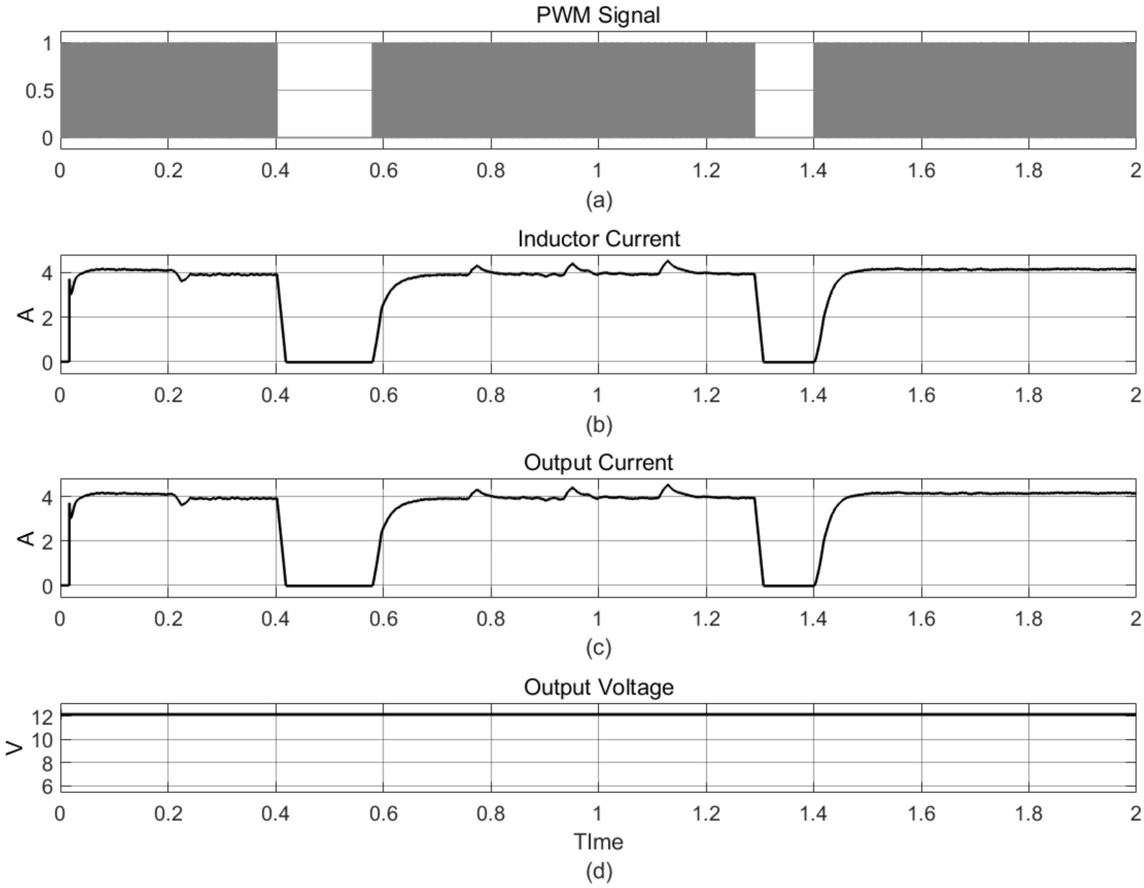

Fig. 4.8 (a) PWM signal, (b) Inductor Current, (c) Output current and (d) Output voltage of PMU2 for Irradiation Pattern 1.

PMUs switched on and TC_3 starts counting the time. When TC_2 reaches the target time Tref it adds 1 to Flag and check whether the irradiance condition has been changed. The irradiance level is still 600W/m^2 and because the Flag is now at 1, then PMU3, PMU4 are switched off keeping the other PMUs switched on for a brief perod of time. Now the irradiance is at normal level and therefore all the PMUs are back in charging state. PWM signal, Inductor Current, Output current and Output voltage of PMU1 and PMU2 for Irradiation Pattern 2 are shown in Fig. 4.10 and Fig. 4.11 respectively. The observations are similar to Irradiation Pattern 1 which confirms the effectiveness of the control scheme.

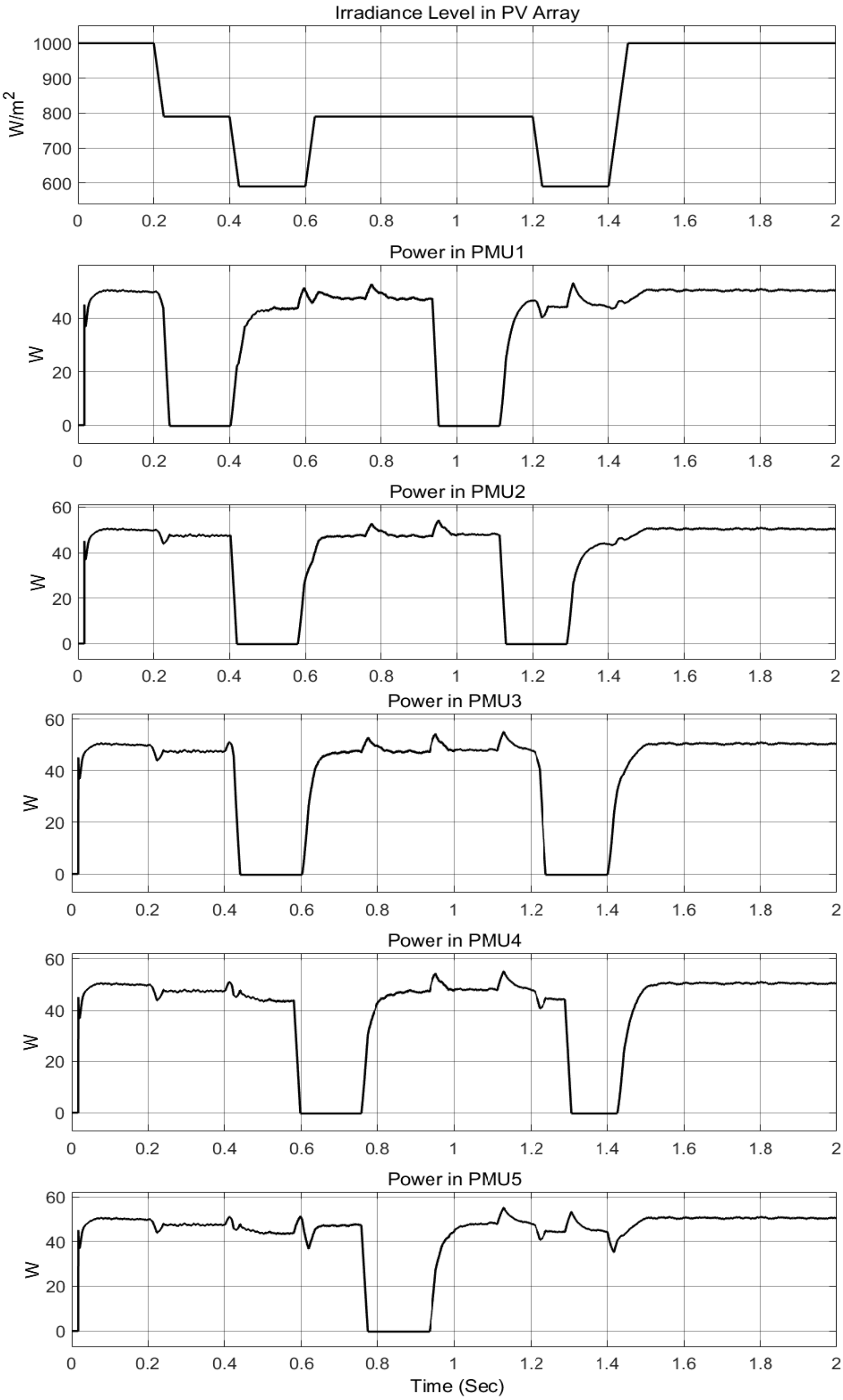

Fig. 4.9 Simulation results for five identical PMUs with 12V batteries and 250kHz switching frequency while 100kHz switching frequency is used in the active switches of the Fanout Node for Time Slot based Algorithm for Irradiation Pattern 2. PMUs are shut down sequentially with the fall of irradiance level.

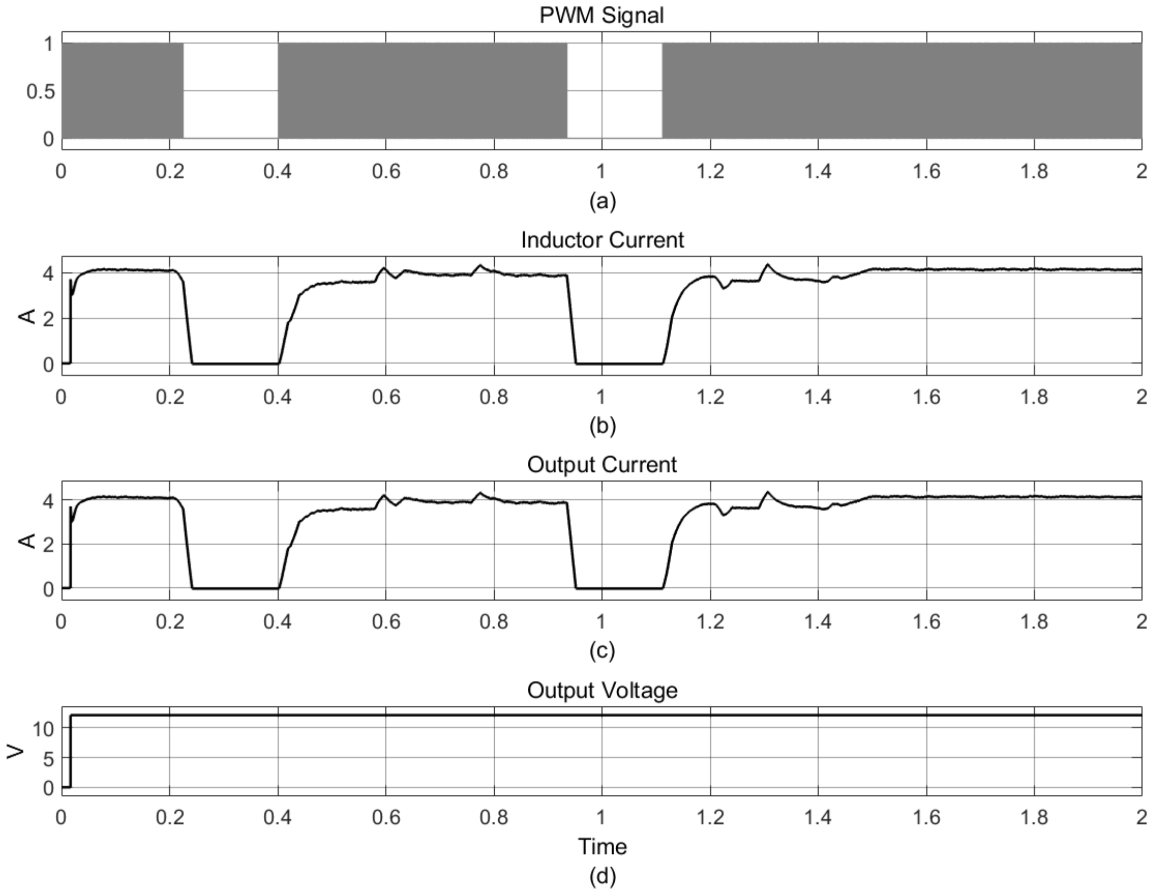

Fig. 4.10 (a) PWM signal, (b) Inductor Current, (c) Output current and (d) Output voltage of PMU1 for Irradiation Pattern 2.

4.4 Comparison between one-way and two-way communication based approach

For five PMUs, one-way communication based approach requires one transmitter and five receivers while two-way communication based approach requires six transmitters and six receivers. The two-way communication based approach may be more intelligent but represents complex circuit structures, whereas one-way communication based approach is a simple and cost effective solution.

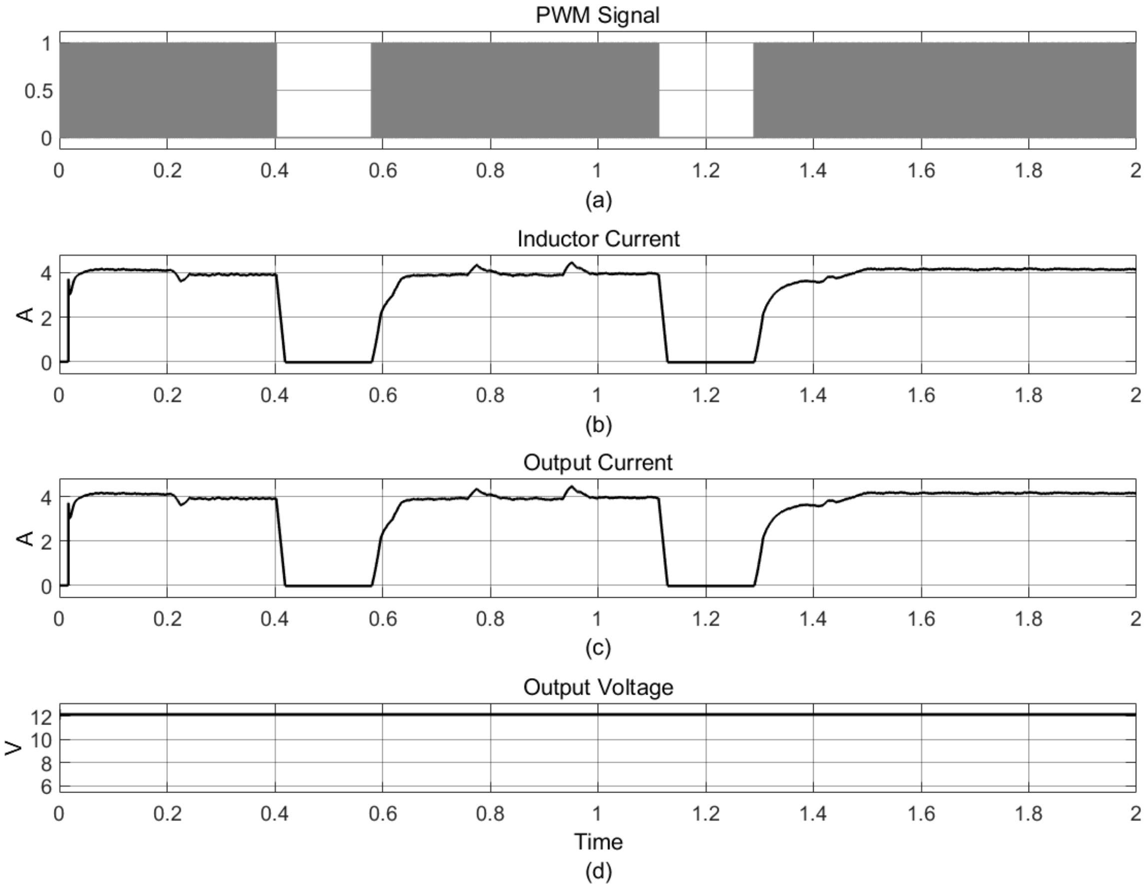

Fig. 4.11 (a)PWM signal, (b)Inductor Current, (c)Output current and (d)Output voltage of PMU2 for Irradiation Pattern 2.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The design presented here is a simplified version of the scalable DC microgrid architecture. The control phenomenon of the load converter and the load side of the home PMU configuration are different from those of the generic structure proposed in [10]. Basic PMW signals are used instead of phase-shifted PWM as the switch control attributes in the PMUs. The look-up table generated from multiple simulations is an attempt to establish a one-way communication method for smart load sharing among different PMUs.

A controllable dc microgrid architecture with an immaculate power flow and sharing control strategy based on a one-way communication topology has been discussed in the previous chapter. The communication-control premise yields to generate a signal to switch on or off a particular PMU on the basis of the present solar irradiance level. A fixed dc bus maintains a lower voltage than the high transmission level to ensure safety of the connected low-voltage batteries and loads. High frequency PWM signals are used to control the fanout node and PMU converters. The PMU configuration follows a generic buck model and five PMUs have been tested for efficiency measurement of the framework. A performance evaluation table generated from multiple simulations subsumes the power efficiency values for different irradiance levels. The Time Slot based Control Scheme increase the effectiveness of the Control Interface in case of long term variation in the irradiance level. The result in different irradiation pattern and temperature confirms the stability of the system. One-way communication-control feature reduces the complexities of the electrical circuits and has been proven to be a reliable and cost effective solution which can have a major effect in popularizing the dc microgrid in the developing countries.

5.2 Future Scope

The Time Slot based Control Scheme makes the DC microgrid more reliable as it ensures equal amount of power sharing among the different PMUs. However, there is always space for improvement in the DC microgrid Architecture. Although the two stage conversion makes the load side more convenient for the customers, single stage conversion can be result in more efficient system. The Full Bridge Converter can be upgraded with new converter models for improvement in the efficiency.

More work can be done in PMUs also. Using bidirectional converters, power can be shared among the PMUs. In that case, if one PMU runs out of charge, other PMUs can supply power to that PMU. A smart metering system will be important for this approach.

The system can be integrated with other renewable energy sources like wind farm or small scale hydro power. The entire system can be turned into a grid connected system so that power can be supplied to the grid in case when there is shortage in generation and there is enough storage in the batteries.

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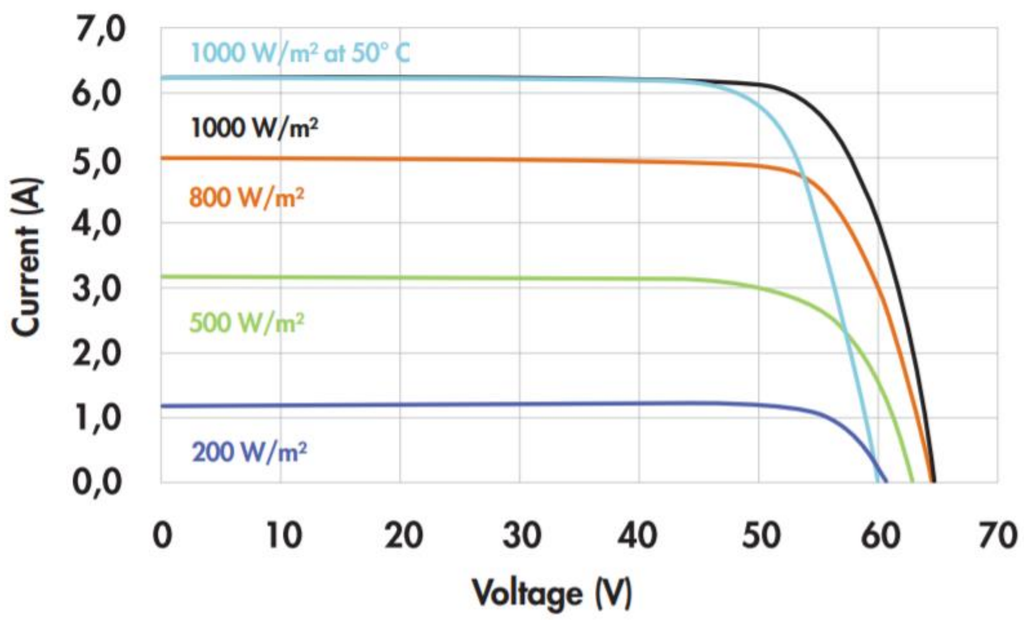
Appendix

Sunpower 315 Solar Panel

Electrical Data Measured at Standard Test Conditions (STC): irradiance of 1000W/m², AM 1.5, and cell temperature 25° C		
Peak Power (+5/-3%)	P_{max}	315 W
Rated Voltage	V_{mpp}	54.7 V
Rated Current	I_{mpp}	5.76 A
Open Circuit Voltage	V_{oc}	64.6 V
Short Circuit Current	I_{sc}	6.14 A
Maximum System Voltage	UL	600 V
Temperature Coefficients		
	Power	-0.38% / K
	Voltage (V_{oc})	-176.6mV / K
	Current (I_{sc})	3.5mA / K
NOCT		45° C +/-2° C
Series Fuse Rating		15 A

Mechanical Data	
Solar Cells	96 SunPower all-back contact monocrystalline
Front Glass	High transmission tempered glass with anti-reflective (AR) coating
Junction Box	IP-65 rated with 3 bypass diodes Dimensions: 32 x 155 x 128 (mm)
Output Cables	1000mm length cables / MultiContact (MC4) connectors
Frame	Anodized aluminum alloy type 6063 (black); stacking pins
Weight	41.0 lbs (18.6 kg)

I-V Curve

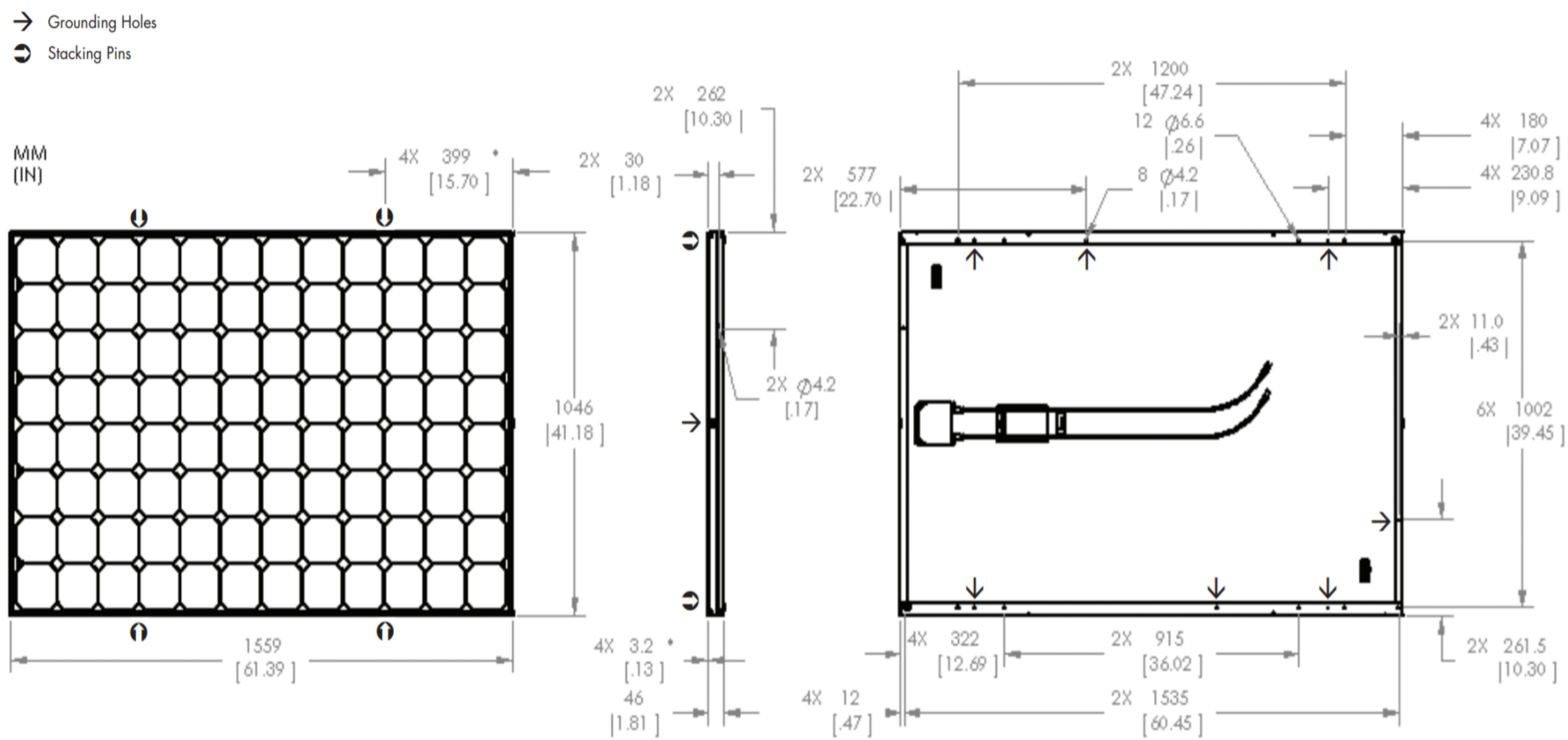


Current/voltage characteristics with dependence on irradiance and module temperature.

Tested Operating Conditions	
Temperature	-40° F to +185° F (-40° C to + 85° C)
Max load	50 psf 245 kg/m² (2400 Pa) front and back – e.g. wind
Impact Resistance	Hail 1 in (25 mm) at 52mph (23 m/s)

Warranties and Certifications	
Warranties	25 year limited power warranty
	10 year limited product warranty
Certifications	Tested to UL 1703. Class C Fire Rating

Dimensions



Grounding Holes
Stacking Pins
MM
(IN)
4X 399 *
[15.70]
1046
[41.18]
1559
[61.39]
2X 262
[10.30]
2X 30
[1.18]
2X Ø4.2
[.17]
4X 3.2 *
[.13]
46
[1.81]
2X 577
[22.70]
2X 1200
[47.24]
12 Ø6.6
[.26]
8 Ø4.2
[.17]
4X 180
[7.07]
4X 230.8
[9.09]
2X 11.0
[.43]
6X 1002
[39.45]
4X 322
[12.69]
2X 915
[36.02]
2X 261.5
[10.30]
4X 12
[.47]
2X 1535
[60.45]

Rahimafrooz Solar Battery Specification

12V Batteries

Battery Type 12V	Capacity AH@10HR	Dimension				Weight (+/- 5%) Kg	
		L	W	H1	H2	Dry	Total
RE15	15	195	126	168	196	4.43	7.42
RE23	23	276	173	213	251	8.7	15.1
RE30	30	276	173	213	251	10.1	16.6
RE40	40	303	171	203	241	12.2	19.1
RE50	55	303	171	203	241	14.04	22.03
RE60	60	413	177	213	253	16.78	26.2
RE70	70	413	177	213	253	19.79	30.16
RE80	80	367	176	290	328	22.96	33.93
RE100	100	367	176	290	328	27.42	37.96
RE130	130	519	276	216	258	34.2	52.5
Battery Type 12V	Capacity AH@20HR	Dimension				Weight (+/- 5%) Kg	
		L	W	H1	H2	Dry	Total
RE135T	135	500	187	417	427	29.2	57.5
RE150T	150	500	187	417	427	31.3	58.6
RE180T	180	500	187	417	427	38.9	67.2
RE200T	200	500	187	417	427	41.9	69.2