Modeling, Designing and Analysis of a Standalone PV DC Microgrid System

Sharaf Sumaiya

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MODELING, DESIGNING, AND ANALYSIS OF A STANDALONE PV DC MICROGRID SYSTEM
by

SHARAF SUMAIYA
(Under the Direction of Adel El Shihat)

ABSTRACT

The increasing concern about global warming, the upsurge of oil prices, and pollution of petroleum energy has led scientists to search for cost-effective energy sources, for example, photovoltaics. Recently DC microgrids have also drawn more consideration because of the expanding use of direct current (DC) energy sources, energy storages and loads in power systems. First, as a groundwork, the 1D organic solar cell has been investigated that leads to design 3D organic solar cell. Then design and analysis of a standalone solar PV system with dc microgrid has been proposed to supply power for both DC and AC loads. The proposed system comprises of a solar PV system with boost DC/DC converter, Incremental conductance (IC) MPPT, bi-directional DC/DC converter (BDC), DC-AC inverter and batteries. The proposed bi-directional DC/DC converter (BDC) lessens the component losses and upsurges the efficiency of the complete system. Additionally, an intelligent control technique has been proposed using fuzzy logic control to the MPPT control for effective operation under non-linear parameter variations for a nanogrid system. Furthermore, a stability analysis of our DC microgrid system is carried out with a boost converter and a bidirectional DC-DC converter and finally, the Lyapunov function for the system has been proposed.

INDEX WORDS: Organic solar cell, MPPT, DC micro-grid, Bidirectional buck-boost converter, Standalone solar PV system, Fuzzy logic controller, Stability analysis.
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by

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To My Beloved Parents
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LIST OF SYMBOLS

\( \varphi_m = \) work function of the metal contact,
\( \chi = \) semiconductor electron affinity,
\( K_B = \) Boltzmann’s contact
\( T = \) Absolute temperature,
\( N_c = \) semiconductor density of states in the conduction band
\( N_v = \) semiconductor density of states in the valence band
\( n_i = \) Intrinsic carrier density.
\( q = \) electron charge
\( N_A = \) acceptor concentration
\( N_D = \) Donor concentration
\( E_g = \) Electronic band gap
\( \mu_n = \) Electron mobility
\( \mu_p = \) Hole mobility
\( d_j = \) Junction depth
\( N_b = \) Background doping concentration
\( N_{A0} = \) Acceptor concentration at boundary
\( \tau_p = \) Hole lifetime
\( \tau_n = \) Electron lifetime
\( \Delta E_t = \) Energy difference between the defect level and the intrinsic level
\( \Delta E_f = \) Quasi-Fermi energy level
\( \varepsilon_r = \) Relative permittivity
\( J_n = \) Current density for electrons
\( J_p = \) Current density for holes
\( D_n = \) Diffusion constant for electrons
\( D_p \) = Diffusion constant for holes

\( G \) = Generation rate

\( U_n \) = Recombination of electrons

\( U_p \) = Recombination of holes

\( V \) = Applied bias voltage

\( V_0 \) = Initial voltage = 0[V]

\( E_c \) = Conduction band energy level

\( E_v \) = Valence band energy level

\( V_a \) = Potential across interfacial layer

\( n_0 \) = Thermal equilibrium densities for electrons

\( P_0 \) = Thermal equilibrium densities for holes

\( n \) = Electron carrier densities

\( p \) = Hole carrier densities

\( I_d \) = diode current (A)

\( V_d \) = diode voltage (V)

\( I_0 \) = diode saturation current (A)

\( T \) = Cell temperature (K)

\( n_i \) = Diode ideality factor

\( N_{cell} \) = Number of cells connected in series.
CHAPTER 1

INTRODUCTION

1.1 Overview on Organic Solar Cell (OSC)

The sun delivers about 174 quadrillion watt-hours of energy onto the earth in every hour, which is higher than the energy demand of the entire human population in one whole year. Solar energy is the source of fresh, plentiful, harmless and environment-friendly energy (Haque, 2012).

Nowadays, the organic solar cells (OSC) is acknowledged as an up-and-coming technology because of its simple fabrication method, cost effectiveness, excellent mechanical properties, thermal budget and high processing speed. However, there are still some concerns that should be addressed. Although indium tin oxide (ITO) substitution has been started as a transparent electrode, these new activities are yet to be executed since these initiatives are in their nascent phase. Additionally, for the preparation of conjugated polymers in OSCs, toxic and halogenated solvents are utilized, which should be substituted by more harmless solvents (Habib, 2012). For the massive area production of OSCs, one of the essentials that must be considered is environmental friendliness. Furthermore, for the roll to roll production of large area OSCs, it is necessary to improve the registration throughout roll to roll procedure because it is utilized to adjust the various layers. Inkjet printing is considered to be the following emerging solar cell fabrication technology because of high material utilization rate, cost-effectiveness, and flexibility. An active layer of Poly (3-hexylthiophene): [6, 6] phenyl C61-butyric acid methyl ester (P3HT: PCBM) has been developed in polymer solar cells by using inkjet printing (Aernouts, 2008). Inkjet-printed OSCs have a great future ahead, however, we need to address the challenges of utilizing inkjet printing technique. There is research going on to improve the efficiency of inkjet-printed OSCs as well as to solve the coffee ring effect, viscosity limitations, film uniformity, nozzle clogging, etc.
1.1.1 Halogen Free Inkjet-Printed OSCs

Organic Photovoltaic Cells possess a huge potential for the next generation renewable energy field. For commercialization OPV, two basic things should be considered. One is to elect a faster and economical production method, and another is the notion that the selected method should be eco-friendly. The recently introduced production method by inkjet printing is compatible in both ways. But one concern is that, in the lab, for the solution processing of OPV using inkjet printing, still halogenated solvents are used, which will not be eco-friendly in large-scale production (He, 2012). So for industrialization, an alternative deposition method is required using halogen-free solvents. Most recently Zhang et al. have presented a state of art OSCs using non-halogenated solvents having nearly 9% efficiencies. Here we highlighted more specifically inkjet-printed OSCs using non-halogenated solvents. Recently, by using the combination of several aromatic based solvents with additives, for instance, di-iodooctane, researchers get an auspicious result. A maximum efficiency is recorded up to 2.7% for an OPV produced using a poly[9,9-diocetylfluorenyl-2,7-dyil-co-10,12-bis(thiophene-2-y)-3,6-dioxooctyl-11-thia-9,13-diazacyclopenta[b]triphenylene](PFDTBTP) photo-active polymer inkjet printing from non-halogenated solvents whereas using halogenated solvents the efficiency reached up to 3.5%. So the efficiency of the OPV produced with halogen-free solvents is still lower. Typical devices can be made of printed PEDOT: PSS (PEDOT) as hole transport layer and poly (3 hexylthiophene):phenyl-C61-butyric acid methyl ester (P3HT: PCBM) utilizing halogen-free solvents. Researchers recently confirmed that this kind of device has overall performance identical to the devices having photo-active layer from spin-coated with ortho-dichlorobenzene (Ren, 2012).

Lim, Guan-Hui, et al. demonstrated a new halogen-free solvent strategy, which is capable of producing desired film macromorphology and good nanomorphology in regioregular poly (3 hexylthiophene): phenyl-C61-butyric acid methyl ester (P3HT: PCBM) model films. The key to this strategy is a good volatile solvent combined with a less volatile miscible poor solvent. This technique is the total reverse of typical low high-boiling-point solvent methodology. They examined four solvent systems which are: chlorobenzene (CB), o-dichlorobenzene (DCB), 3:3:4 vol/vol (v/v) butylbenzene: mesitylene:
chlorobenzene (BB: MS: CB), and 8:2 v/v butylbenzene: toluene (BB: TOL). The initial two have regularly been utilized to print P3HT: PCBM and another polymer: fullerene films. The last two solvent systems are combinations that they have created to outline their solvent procedure to print P3HT: PCBM. They got the best inkjet-printed P3HT: PCBM cells with power conversion efficiency of 2.2% versus 1.3% announced for tetraline and which is around seventy-five percent of that found in the normal spin-coated cells from CB or DCB having the same photoactive layer synthesis and thickness. This demonstrates a noteworthy improvement for non-halogenated solvents, even though there is still extension for further refinement (Lim, 2014).

In another study by Eggenhuisen et al. the use of inkjet printing for depositing four layers of the OPV cell by replacing hazardous halogenated solvents with more considerate non-halogenated solvents in ink preparation was investigated. They showed that inkjet-printed photoactive layers with non-halogenated solvents combinations have merely performance losses in comparison with layer spin-casted from chlorobenzene. They made cells having four and three inkjet-printed layers individually using an active area of 1 cm² and 2.0 mW/cm². Also, they made a vast area module containing 92 cm² functional region having an efficiency of 0.98% (Eggenhuisen, 2015).

1.1.2  ITO-Free Inkjet-Printed OSCs

Several ITO have a transparency of 90.2% and conductivity of $\sigma = 7.2 \times 10^{-4}$ W·cm [65]. Due to these extraordinary properties of ITO, it has been broadly employed as a transparent electrode for organic or polymer light emitting diode (OLED/PLED) and organic photovoltaics (OPVs). But it has some drawbacks also, such as applying in large devices, it is possible to have cracks or delamination and conductivity losses with bending [68]. Again paucity and expensiveness are also major shortcomings. So the objective is to find highly conductive, flexible, transparent and cost-effective material. Various endeavors to replace ITO, especially in OSCs, have been published, for instance, carbon nanotubes (CNTs), graphene, PEDOT: PSS [poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate)], ultra-thin metal layers.

Hösel et al. show that flextrode substrate which consists of silver-grid/PEDOT: PSS/ZnO is an appealing ITO-free alternate for the quick fabrication of inverted-structure OSCs. They also explained how
this flextrode substrate is handled at high speed by printing some layers simultaneously utilizing inline coating and printing. The sheet resistance of the joined silver grid and PEDOT: PSS stack is nearly six times lower than commonplace adaptable ITO-coated Polyethylene terephthalate (PET) substrate. They successfully produced completely R2R-prepared solar cells and modules with more than 1.8% PCEs on single cells, 1.6% PCE on the active layer and 60% of FFs (Hösel, 2013).

Burgués-Ceballos et al. replaced indium tin oxide (ITO) in OSCs by inkjet-printed silver grids and showed that the ITO-free solar cells indicated marginally higher performance over the ITO built reference. The most noteworthy FF got in this study was 67%, and JSC is nearly the same concerning the ITO-based application, which demonstrates that the grid structure has an indistinguishable current collecting ability from ITO. But still, the PCE is lower than anticipated. It is inferred that JSC is the fundamental driver of this and also great correction in open-circuit voltages (VOC) are acquired. Hence different elements other than the anode might be responsible (Burgués-Ceballos, 2014).

1.1.3 Roll-to-Roll Printing of OSCs

Recently, the requirement for economic and quick preparing of vast areas of thin organic cells has turned into an undeniably vital objective inside various research fields. Large area OPV cells are anticipated to add to energy harvesting when incorporated in exteriors, greenhouses, structures or broad daylight transport. In this situation, R2R fabrication of OPV will encourage the high throughput at diminished expenses for these applications. Recently, the fabrication of top standard conductive silver structures utilizing inkjet printing in fast R2R processing has been shown for various electronic devices. These most recent improvements convey R2R inkjet printing of OPVs a step closer by demonstrating the usefulness of making these devices reliably utilizing a high-volume roll-to-roll technology.

Impedance in lab scale, inkjet printers have a limited set of nozzles, which make printers slow to print large areas. It is shown that 3.5 cm width of industrial printhead allows printing of huge areas that are compatible with the R2R production of OPVs. The capability of inkjet printing for a huge area of OPV was exhibited by the creation of a module with 92 cm2 active area that demonstrated the efficiency of 0.98%
1.2 Efficiency Improvement Strategies of OSCs

Significant improvements of the organic solar cells in their power conversion efficiency can be controlled by their morphological properties. Polymer-fullerene blends morphology of OPVs could be considerably controlled over the selection of annealing conditions, polymer donor chemical properties, drying rate, and solvent.

1.2.1 Efficiency Improvement of OSCs by Energy Conversion Layer

Bin Yeol et al used a rubrene layer as an energy conversion layer (ECL). The proposed OPV consisted of an aluminum layer of 100 nm as an electrode, a poly (3,4-ethylene dioxythiophene)-poly (styrene sulfonate) (PEDOT-PSS) layer with the thickness of 100 nm, P3HT: PCBM layer of 80 nm, a glass substrate, and rubrene (5, 6, 1, I 2 tetraphenyl tetracene) layer to enhance OPV device performance. The layer was fashioned on the outer surface of the organic photovoltaic cell. To re-emit visible light and absorb ultraviolet light; rubrene layer was used which acted as a spectral down-conversion layer. Concerning the thickness of the rubrene layer, the Power Conversion Efficiency of the OPV cell has been investigated by the team and about 1.5 times increase in the efficiency was recorded, at the time the thickness of the rubrene layer 295 nm was compared to the OPV device without rubrene layer (Yeo, 2015).

1.2.2 Efficiency Improvement by Vapor and Thermal Annealing

The efficiency of organic and inorganic solar cells can be improved notably by solvent vapor annealing and/or thermal annealing. Following these annealing techniques Chen et al observed a significant improvement in organic small molecule solar cells (OSMSCs), which consist of several layers, e.g., ITO/PEDOT:PSS/p DTS(FBTTh2)2:PC71BM/PFN/Al, where p-DTS(FBTTh2)2 is 7,7-(4,4-bis(2-ethylhexyl)-4H silolo[3,2-b:4,5-b]dithiophene-2,6-diyl)bis(6-fluoro-4-(5-hexyl-[2,2- bithiophen]-5-y)benzo[c][1,2,5]thiadiazole), PC71BM is [6,6]-phenyl C71 butyric acid methyl-ester PFN is poly[(9, 9-bis(3-(N,N-dimethylamino)propyl)-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene)], Al is aluminum. The overall device performance improved additionally while thermal annealing treatment is done after the solvent vapor annealing treatment.
The optimized devices showed a PCE of 8.22% and the simultaneous improvement of the device parameters (with a VOC = 0.80 V, short-circuit current (JSC) = 15.2 mA cm\(^{-2}\), and fill factor (FF) = 67.7%). Solvent vapor annealing (SVA) can also enhance the efficiency, but, there will be a decrease in open-circuit voltage (VOC). The utilization of SVA will be able to guide to enhance the magnitude in hole mobility, that is very useful for charge collection as well as transport, but also liable for a decrease of VOC because of depleted constant carrier density. The lessening of VOC is possible to avoid successfully if the devices have been treated with subsequent thermal annealing that was revealed to be a recommended change in charge dynamic. This is how it leads to high overall device performance and increases VOC. As a result, the two-step annealing processes, Solvent Vapor Annealing (SVA), and thermal annealing are corresponding to each other. Those can likewise give reasonable courses to enhance the VOC, current density, fill factor and power conversion efficiency of small organic molecule solar cells (Chen, 2016).

1.3 Concept of microgrid

A microgrid is a small-scale grid system that can work freely or in conjunction with the region's principal electrical grid. Any small confined station with its energy sources, generation and loads and perceptible limited boundaries qualify as a microgrid. Today, microgrid is picking up a considerable measure of desirability since new renewable energy sources that occasionally work better nearer to the point of cause instead connected to the main electrical grid. The best illustration is a photovoltaic system (Haque, 2012).

Nowadays, more houses and structures are associated with small neighborhood solar energy grid frameworks that may serve only one property. Besides, as solar innovation descends in cost and turns out to be more viable, a few features can really get advantageous by a smaller economy of scale — straightforward solar cells put in accessible territories can take in free regular daylight and change it over to electrical energy to run a specific arrangement of machines, or warming and cooling frameworks. The microgrid alludes to a small-scale power grid that can keenly succeed in managing energy exchange between the interconnected loads and the distributed generation sources, for example, PVs (Arifin, 2013). Microgrids can be proposed as backup power generation or to support the principle electrical grid amid
times of substantial demand. Frequently, microgrids include different energy sources as a method for consolidating sustainable power. Different purposes incorporate lessening costs and upgrading reliability.

There are two fundamental sorts of microgrid; DC microgrid and AC microgrid.

1.3.1 DC microgrid

Figure 1-1 demonstrates a schematic perspective of the DC microgrid system. This framework uses a DC bus as its primary support and allocates power to a group that comprises a few handfulls or a hundred of family units in a neighborhood.

Solar cells, fuel cells, batteries, etc. are the energy sources of a DC microgrid to deliver power to loads. To change DC voltages to the rated DC voltage, a buck or boost converter has been utilized in the microgrid. To uphold reference output voltage, a DC-DC converter is controlled by a proportional integral (PI) controller.

1.3.2 The Photovoltaic system in DC microgrid

Sunlight has been converted to dc power by the solar cells. The photovoltaic cell produces electricity from the sun. At the point when PV panels are visible to daylight, it changes the sunlight or solar energy into electrical energy. PV array is a mixture of parallel and series photovoltaic cells. This cluster builds up the power from the sunlight/solar energy in a straightforward manner, and it changes when the temperature and
irradiances changes.

In the figure 1-2, a block diagram of a PV system has been shown. PV systems consist of an MPPT algorithm for tracking the maximum power from PV panels, DC-DC converter (boost converter) to boost the voltage of PV to rated voltage, finally, through the inverter, it connects with the loads.

1.3.3 DC-DC Boost converter

The boost converter is a sort of DC-DC converter that has a yield voltage more noteworthy than the provided input voltage. Figure 1-3 given underneath shows typical DC-DC converters. The DC-DC converters are used as a part of a ton of utilization where the supplied energy isn't sufficient for the activity of such applications. There are two kinds of DC-DC converters, buck converter, and a boost converter. Much the same as the boost converter, the buck converter adjusts the extent of the voltage provided to it yet for this situation the yield voltage is lower than that of the supplied input voltage.
1.3.4 Maximum Power Point Tracking (MPPT)

In order to address the issue of poor efficiency of a PV system, a few strategies have been proposed, among which another idea is named, "maximum power point tracking" (MPPT). All MPPT techniques have a similar objective to maximize the PV array output power by tracking the maximum power on each working condition.

Various MPPT methods have been produced such as Perturb and Observe (P&O), incremental conductance (IC) algorithm, fuzzy logic, etc. The most generally utilized calculations are the P&O and IC algorithm. The P&O algorithm is known because of its secure execution; however, it diverges from and vacillates around the maximum power point (MPP), thus deteriorating a significant quantity of the existing power.
1.3.5 Bi-Directional buck-boost converter

One kind of DC-DC converter is the buck-boost converter which provides an output voltage value either more than or not as much as the input voltage value. The yield voltage is adaptable in view of the duty cycle of the switch (MOSFET). Along with that, a bi-directional buck-boost converter additionally gives reversal of power stream. A bidirectional component of this converter makes it possible to flow the power from input to output side.

1.3.6 DC to AC converter (Inverter)

For supplying power to the AC loads, we have incorporated a DC to AC converter (inverter) into our microgrid system. An inverter changes direct current to alternating current from a DC power source which is helpful in power electronics and electrical apparatus rated as AC voltage. Additionally, they are broadly utilized as a part of the switched mode power supplies inverting steps. Inverters cannot produce power by themselves it takes power from the DC sources and converts it to AC. The circuits are arranged to agree on the switching innovation and switch nature, waveform, frequency, and yield waveform.
The fundamental circuits incorporate an oscillator, drive circuit and control circuit for the power and switching devices and a transformer. The change of DC to AC voltage is accomplished by changing energy of the DC source, for example, the battery, or from a rectifier yield, into an alternating voltage. This is done utilizing switching devices which are uninterruptedly turned on and off, and after that stepping up utilizing the transformer. There are a few setups which don't utilize a transformer (Islam, 2014).

1.3.7 Energy Storage Devices (Battery)

The electricity grid is a very complex framework in which power supply and demand has to be equivalent at any given instant. Steady acclimations to the supply are required for expectable variations of the demands, for example, day by day human actions, and in addition sudden changes from equipment overload, natural calamities and so on. Energy storage systems play an essential part in this balancing act as well as make a more adaptable and dependable grid system. For instance, while having more supply than demand, during the night when minimal cost power plants keep on operating, the surplus electricity can be fed to power the storage devices. At the point when demand is more than supply, storage facilities can release their stored energy to the stored energy. Some sustainable generation systems, for example solar and wind electricity generation systems, have variable yields. Therefore, improvements in the storage technology have incredible potential for smoothing out the power supply from these sources and guaranteeing that the supply of generation matches the demand. The total battery effectiveness gives the measurement of the efficiency of a sustainable energy system, where a sustainable power source has to be
utilized as productively as possible. The battery charge-discharge effectiveness has the ultimate impact on the total efficiency.

1.3.8 Lead-acid batteries:

Lead acid batteries are marginally economic however they have significant space and maintenance necessities. They additionally have a short lifespan, which diminishes quickly if the battery is discharged below 30%. This outcome in the diminishment of energy density adding up to expanded capital expenses. They are usually introduced in uninterruptible power supply systems and renewable energy systems. The biggest one introduced is 40 MWh framework in Chino, California. Some of the major limitations of these types of batteries are the requirement of frequent maintenance, cost compared to the traditional choices, and it’s heavy owing to the utilization of Pb. The qualities of overwhelmed lead-acid batteries are their relatively long-life, commercial accessibility and durability.

1.3.9 Nickel metal hydride battery

Photovoltaic power outputs change with climate at each minute. Batteries can help the grid connection of these systems’ power sources by balancing out the fast output fluctuations. It is normal that batteries with bigger capacity and higher charge/discharge rates will be created for making sustainable power sources more serviceable. Nickel metal hydride batteries can be established with large capacity limits empowered by its three-dimensional bipolar structure, high rate charge and discharge capability, and long cycle strength. This battery is an environment-friendly one without harmful metals, for example, lead, mercury, cadmium et cetera. Nickel hydroxide is utilized as the positive anode, and metal hydride is utilized as the negative electrode. Furthermore, it can be easily recycled because it has no welding connection. The voltage of a stack is effectively changed as per the number of associated cells in the stack. The capacity of every cell (Ah) is effectively extended by changing the size and the quantity of electrodes in the cell (Terada, 2008).
1.4 Objectives of Thesis

Renewable energy sources especially solar systems are gaining more interest day by day as it is ecofriendly. The main objective of this thesis is to investigate and model the new design of organic solar cells to maximize the efficiency of solar energy which leads us to design a complete standalone solar PV system with dc microgrid. The system was designed to feed a fixed DC load of 1KW and fixed AC load of 8KW, 500KVAR load which can be assumed as a small area that can be powered from this standalone DC microgrid without depending on the main grid connections. To enhance the PV array efficiency, a fuzzy logic MPPT controller has been utilized to track the maximum power from a PV panel for a nanogrid system. The next step is to analyze the stability of the DC microgrid system. The Lyapunov function has been figured out utilizing SOSTOOL.

1.5 Thesis Organization

Chapter 2 describes the modeling and analyzing of a one-dimensional solar cell with the P3HT (poly (3-hexylthiophene)): PCBM (phenyl-C61-butyric acid methyl ester) material to illustrate how the material’s characteristics link to the electrical properties based on the Shockley-Read-Hall recombination and carrier generation model. Then, designing a three-dimensional model with a new inverted design of an organic solar cell using P3HT: PCBM and silver grids, for light trapping.

Chapter 3 proposes a design and analysis of a standalone solar PV system with a DC microgrid. A DC-DC boost converter interfaces with the proposed system to step up the PV array voltage and keep up steady output voltage. The fluctuation nature of a PV array makes them inadmissible for independent activity. To overcome the disadvantages an energy storage device is utilized as a part of the proposed framework to remunerate the fluctuations and to keep up a smooth and ceaseless power stream in every working mode to loads. Bi-directional DC-DC converter (BDC) is equipped for changing energy between two DC buses. It can work as a boost converter which supplies power to the load when the PV system’s yield power is more prominent than the required load power. It likewise works in buck mode which charges from the DC buses when yield power is not as much as the necessary load power. The proposed converter
lessens the component losses and upsurges the efficiency of the complete system. The total system is designed and executed in MATLAB/SIMULINK environment.

Chapter 4 introduces a fuzzy logic MPPT controller to track the maximum power from the PV array as the fuzzy logic MPPT is more robust and its simple design gives less overshoot. We showed that the simulation results using FLC is almost the same as the PV panel which means the system is taking maximum power from the PV array. After that, a stability analysis of the two controllers has been carried out.

Chapter 5 discusses the conclusions of the research and a discussion of future work.
CHAPTER 2
MULTIDIMENSIONAL MODELING OF ORGANIC SOLAR CELL

2.1 Abstract

Modeling and analysis of multidimensional organic solar cells (OSCs) with different geometry design can give the researchers an opportunity to explore the electrical and optical properties of the OSCs, enhance the cell efficiency, and then take it to the implementation of the new design. In this chapter, we first model and analyze a one-dimensional solar cell with the P3HT (poly (3-hexylthiophene)): PCBM (phenyl-C61-butyric acid methyl ester) material to illustrate how the material’s characteristics link to the electrical properties based on the Shockley-Read-Hall recombination and carrier generation model. Then, we extend the design to a three-dimensional model with a new inverted design of an organic solar cell using P3HT: PCBM and silver grids, for light trapping.

2.2 Introduction

The increasing global demand for energy has urged scientists to explore new alternatives to conventional resources over the past few decades, and organic solar cells (OSCs) have become one of the most attractive options due to its power flexibility, low-cost potential, attractive thermal budget, and simple preparation methods. Although OSCs have different promising technological advantages such as semi-transparency, solution processing and flexibility compared to the conventional inorganic solar cells; however, there remain some concerns that should be addressed. Historically, the OSCs do not offer high conversion efficiency, and there remain significant scientific efforts to devote to designing OSCs with maximum efficiency (Bhaumik, 2014). One of the significant challenges to improve the conversion efficiency is to model the OSCs accurately. Therefore, the study and analysis of the precise multidimensional modeling of OSCs are of substantial scientific interests at present. In this work, we illustrate the multidimensional (1-D and 3-D) modeling of an OSC. We used P3HT: PCBM solar cell for the modeling due to their lightweight, large-area fabrication, low cost and good conversion efficiency (up to 4.24%). P3HT is among the Polythiophene family which is a very conductive polymer material, and the
excitation of the \( \pi \)-orbit electron under the solar illumination in P3HT provides an excellent photovoltaic effect in the OSC. On the other hand, PCBM is a fullerene derivative, which has high hole mobility (Hacène, 2014). Therefore, we have used this layer as an electron acceptor in the OSC that has been used for the multidimensional modeling in this study. We used the built-in Shockley-Read-Hall recombination model along with the Analytic Doping Model feature for n-type doping and the Geometric Doping Model Feature for p-type surface doping in the 1D model analysis. To obtain a more comprehensive picture of the P3HT: PCBM solar cell we used 3D modeling to demonstrate both the optical and electrical properties by using the semiconductor module in COMSOL upon solving the Poisson's equation for the electric potential and the drift-diffusion equations for electrons and holes.

2.3 1D modeling of P3HT: PCBM organic solar cell

Here we design a solar cell model which consists of 1D P3HT: PCBM p-n junction that incorporates a Shockley-Read-Hall recombination and carrier generation. Usually, in P3HT: PCBM solar cells, the photo-generated carriers are cleared to each side of a p-n junction’s depletion region. We would then be able to separate electrical power by applying a little forward bias to the solar cell. From the product of applied voltage and photocurrent, we can determine the power. The objective of the model is to predict a P3HT: PCBM solar cell’s performance under the forward bias and an applied voltage from 0 and 0.6 V.

We opt to investigate the P3HT: PCBM p-n junction, which we shape by p-doping the front surface of an n-type P3HT: PCBM wafer. This n-type P3HT: PCBM wafer is formed by uniform mass n-doping which is anticipated to be 1016 cm\(^{-3}\). The peak concentration of the front surface p-doping has been assumed to be 5×10\(^{18}\) cm\(^{-3}\) and a Gaussian drop off with a junction depth of 0.5 \( \mu \)m. The two types of
doping, a front surface, and uniform bulk are effortlessly represented by separately utilizing a Geometric Doping Model and an Analytic Doping. We employ a Boundary Selection for Doping Profile node to characterize the surface and add two Metal Contact highlights to indicate the electrical connections between the front and back covers.

We account for the main recombination effect with the Shockley-Read-Hall Recombination model, implemented via the Trap-Assisted Recombination. For simplicity of the model, the generation rate is left to be User-Defined.

2.3.1. Definition of the Model

This 1D model domain is 50 um in length having a cross-sectional area of 1 cm2. We use the built-in Shockley-Read-Hall recombination model having a cross-sectional area of 1 cm2. The Shockley-Read-Hall recombination model used in this work is given below (Goudon, 2007).

\[ \nabla \cdot (\varepsilon_r \nabla V) = q(n - p + N_A^- - N_D^+) \]
\[ -\frac{1}{q} \nabla J_n = -U_n, \quad -\frac{1}{q} \nabla J_p = -U_p \]
\[ J_n = \left( \mu_n \nabla E_c + \frac{qD_{n,\text{th}}}{T_i} \nabla T_i \right) n + \mu_n K_B T_i G(N/N_c) V_n \]
\[ J_p = \left( \mu_p \nabla E_v + \frac{qD_{p,\text{th}}}{T_j} \nabla T_j \right) p - \mu_p K_B T_j G(N/N_v) V_p \]
\[ E_c = -q(V + \chi), \quad E_v = -q(V + \chi + E_g) \]

The photo-generation is user-defined. The P3HT: PCBM material data will be discussed in the next section. For n-type doping, we utilize the feature of Analytic Doping Model, and for the p-type surface doping, the Geometric Doping Model has been used. The Geometric Doping Model is shown below (Cuevas, 1989).

\[ N_A = N_A^{\text{prev}} + N_{A0}, \quad N_D = N_D^{\text{prev}} \]
\[ N_A = N_A^{\text{prev}} + N_{A0} \exp\left[-\left(\frac{L}{d_j}\right)^2\right] \]
\[ I_d = \frac{d_j}{\sqrt{\ln\left(|\frac{N_{A0}}{N_b}|\right)}} \]

Trap-Assisted Recombination parameters are shown below (Sun, 2016).
\[ R_n = \frac{np - \gamma n_Y n_i \varepsilon_{\text{eff}}}{T_p(n + n_1) + T_n(p + p1)}, R_p = R_p \]

\[ n_1 = \lambda n_i n_{\text{eff}} \exp \left( \frac{\Delta E_t}{K_B T} \right), P_1 = \lambda p n_i n_{\text{eff}} \exp \left( -\frac{\Delta E_t}{K_B T} \right) \]

\[ n_{\text{eff}} = \sqrt{N_c 0 N_v 0 \exp \left( -\frac{E_g - \Delta E_g}{2K_B T} \right)} \]

\[ \Delta E_t = E_t - E_i \] (2.3)

The electrical connections to the front and back surfaces are realized with two Metal Contacts (Sze, 2006).

\[ V = V_a + \frac{K_B T}{q} \arcsinh \left( \frac{N_D - N_A}{2n_i} \right) - \chi - \left( \frac{E_g}{2q} - K_B T / 2 q \ln (N_V / N_C) \right) \]

\[ n = \frac{1}{2} (N_d^+ - N_a^-) + \frac{1}{2} \sqrt{\left( N_d^+ - N_a^- \right)^2 + 4 \gamma n Y p n_{\text{eff}}} \]

\[ p = n = \frac{1}{2} (N_d^+ - N_a^-) + \frac{1}{2} \sqrt{\left( N_d^+ - N_a^- \right)^2 + 4 \gamma n Y p n_{\text{eff}}} \] (4)

\[ V = \frac{K_B T}{q} \left( \ln \left( \frac{n}{N_D - N_A} \right) + \frac{1}{2} \ln \left( \frac{N_V}{N_C} \right) \right) - \frac{1}{q} \left( \Delta E_f + \frac{1}{2} E_g \right) - \chi + V_0 \]

\[ \Delta E_f = \frac{K_B}{2q} \left( T \ln \left( \frac{N_V(T)}{N_C(T)} \right) - T_0 \ln \left( \frac{N_V(T_0)}{N_C(T_0)} \right) \right) + \chi^0(T_0) - \chi^0(T) + \frac{1}{2q} \left( E_g^0(T_0) - E_g^0(T) \right) \]

\[ J_n, n = -qV_n(n - n_0), \quad J_p, n = -qV_p(p - p_0) \]

\[ n_0 = N_c \exp \left( -\frac{\varphi_m - \chi}{K_B T_i} \right), \quad P_0 = N_V \exp \left( \frac{E_g - \varphi_m + \chi}{K_B T_i} \right) \]

\[ V = -\varphi_m - \frac{1}{q} \Delta E_f + V_0 \]

The default Physics-controlled mesh type is used with the element size set to “Finer.” The voltage sweep is carried out using a Stationary study with Auxiliary sweep enabled.

2.3.2. P3HT: PCBM materials properties:

Luckily, the majority of the parameters in (1-4) can be acquired or deduced from published work in the literature. For example, the bandgap of the P3HT: PCBM mix Eg = 1.1 eV could be acquired from the difference between the HOMO (Highest Occupied Molecular Orbital) of P3HT (−5.1 eV) and the LUMO (Lowest Unoccupied Molecular Orbital) of PCBM (−4 eV).
The effective static dielectric permittivity $\epsilon_r = 3.4$ can be obtained from the weight ratios between P3HT and PCBM, where their static relative dielectric permittivity is 3 and 3.9, respectively (Koh, 2011). The fluorescence lifetime $\tau(0)$ is 25 ns.

Table 1: Materials properties of P3HT: PCBM

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Parameter symbol</th>
<th>Numeric Value</th>
<th>Remarks/Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOMO level</td>
<td>$E_{0p}$</td>
<td>-5.1 eV</td>
<td>(Koh, 2011)</td>
</tr>
<tr>
<td>LUMO level</td>
<td>$E_{0n}$</td>
<td>-3.9 eV</td>
<td>(Koh, 2011)</td>
</tr>
<tr>
<td>Electronic band gap</td>
<td>$E_g$</td>
<td>1.2 eV</td>
<td>HOMO of P3HT (~5.1 eV) and the LUMO of PCBM (~3.9 eV)</td>
</tr>
<tr>
<td>Electron mobility</td>
<td>$\mu_n$</td>
<td>$2 \times 10^{-3}$ cm$^2$/V.s</td>
<td>(Koh, 2011)</td>
</tr>
<tr>
<td>Hole mobility</td>
<td>$\mu_p$</td>
<td>$4 \times 10^{-4}$ cm$^2$/V.s</td>
<td>(Szymtkowski, 2009)</td>
</tr>
<tr>
<td>The effective density of states, valance band</td>
<td>$N_V$</td>
<td>$1.35 \times 10^{22}$ cm$^{-3}$</td>
<td>(Scharber, 2006)</td>
</tr>
<tr>
<td>The effective density of states, the conduction band</td>
<td>$N_C$</td>
<td>$1.35 \times 10^{22}$ cm$^{-3}$</td>
<td>(Scharber, 2006)</td>
</tr>
<tr>
<td>Effective static dielectric permittivity</td>
<td>$\epsilon_r$</td>
<td>3.4</td>
<td>(Koh, 2011)</td>
</tr>
<tr>
<td>The fluorescence lifetime</td>
<td>$\tau(0)$</td>
<td>25 ns</td>
<td>(Scharber, 2006)</td>
</tr>
</tbody>
</table>

2.4. Results and Discussions

In Figure 2-1, we make a comparison between donor and acceptor concentrations up to 10 μm underneath the front surface of the organic solar cell. Quite often, when donor concentration remains constant, the acceptor concentration decreases sharply. Here the acceptor concentration remains at a real high level whereas the donor’s concentration remains at a constant value. To maintain a strategic distance from incidental setup blunders, it is a common practice to check the model’s doping profile.
Figure 2-1. Donor and acceptor concentrations (1/cm²) for 10 mm beneath the front surface.

We also investigated the Shockley-Read-Hall recombination rate and user-defined photo generation rate for the whole cell’s thickness, which is shown in figure 2-2 in a semilog plot. The straight line in the plot corresponds to the user-defined single exponential function.
Figure 2-2. Shockley-Read-Hall recombination rate and user-defined photo-generation rate (For the entire cell)

Lastly, the I-V and P-V curves of the solar cell are shown in figure 2-3 and 2-4, respectively. These characteristic curves help us visualize some of the working parameters of the cell, including the maximum power, cut off and open-circuit voltage (~0.3 V). Fill factor can be found from the following equation (Scharber, 2006) using the necessary parameters from the graphs as well as the efficiency of the organic solar cell.

\[ FF = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}} \]
\[ \eta = \frac{I_{sc}V_{oc}FF}{P_{in}} \]

Figure 2-3. I-V curve of the P3HT: PCBM solar cell
2.5. 3D modeling and simulation of OSC

Nowadays, the organic solar cell (OSC) is acknowledged as a promising technology because of its simple manufacture method, cost effectiveness, excellent mechanical properties, thermal budget and high processing speed. Here we also introduce a 3D model, see figure 2.5, and simulation of the organic solar cell using COMSOL Multiphysics. For the optical modeling of the OSC, we plan to obtain the light absorption rate utilizing the wave optics module of the COMSOL. We will solve Maxwell’s equations in the 3D frequency domain using the finite element method in the wave optics module. For the electrical model to find out the quantum efficiency, charge generation, recombination rate, and carrier transport, we opt to use the semiconductor module in COMSOL to solve the Poisson's equation for the electric potential and the drift-
diffusion equations for electrons and holes in a semiconductor material.

2.5.1 Geometry design of the 3D OSC:

The geometry design of the organic solar cell consists of the 100nm thick glass substrate, silver grids (250 nm thick), on top of the silver grid 60nm thick PEDOT: PSS electrode layer. We used a 160 nm thick P3HT: PCBM for the active layer and a 100 nm thick solid silver layer is adopted for the cathode. In this design, the silver grids are 250 nm in height and 100µm in width used for light trapping.

![Geometry model of 3D P3HT: PCBM Solar cell](image)

**Figure 2-5. Geometry model of 3D P3HT: PCBM Solar cell**

2.5.2 Materials of the 3D OSC

The materials we used for the solar cell are shown in figures 2-6 and 2-7 as aforementioned, glass is used for the substrate, P3HT: PCBM for the active layer, PEDOT: PSS for the electrode, silver grid for the anode, and silver for the cathode are adopted.

P3HT: PCBM material properties: When we model a bulk heterojunction (BHJ) organic solar cell, we used P3HT: PCBM for the active layer.

Relative permittivity = 3.4
Electron affinity = -5 ev

Electron mobility = 2*10^{-7} m^2/(V.s)

Hole mobility = 1*10^{-8} m^2/(V.s)

<table>
<thead>
<tr>
<th>Property</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Property group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s ratio</td>
<td>nu</td>
<td>1</td>
<td>Basic</td>
<td></td>
</tr>
<tr>
<td>Band gap</td>
<td>Eg0</td>
<td>1.1*10^{-19} V</td>
<td>Semiconductor material</td>
<td></td>
</tr>
<tr>
<td>Effective density of states, valence band</td>
<td>Nv</td>
<td>1/m^3</td>
<td>Semiconductor material</td>
<td></td>
</tr>
<tr>
<td>Effective density of states, conduction band</td>
<td>Nc</td>
<td>1/m^3</td>
<td>Semiconductor material</td>
<td></td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>epsilonr</td>
<td>3.4</td>
<td>1</td>
<td>Basic</td>
</tr>
<tr>
<td>Electron affinity</td>
<td>chi0</td>
<td>-5*10^{-19} V</td>
<td>Semiconductor material</td>
<td></td>
</tr>
<tr>
<td>Electron mobility</td>
<td>mun</td>
<td>2e-7</td>
<td>m^2/(V.s)</td>
<td>Semiconductor material</td>
</tr>
<tr>
<td>Hole mobility</td>
<td>mup</td>
<td>1e-8</td>
<td>m^2/(V.s)</td>
<td>Semiconductor material</td>
</tr>
</tbody>
</table>

Figure 2-6. Active layer P3HT: PCBM materials properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Property group</th>
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<tbody>
<tr>
<td>Relative permittivity</td>
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<td>Basic</td>
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<tr>
<td>Band gap</td>
<td>Eg0</td>
<td>V</td>
<td>Semiconductor material</td>
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<tr>
<td>Electron affinity</td>
<td>chi0</td>
<td>V</td>
<td>Semiconductor material</td>
<td></td>
</tr>
<tr>
<td>Effective density of states, conduction band</td>
<td>Nc</td>
<td>1/m^3</td>
<td>Semiconductor material</td>
<td></td>
</tr>
<tr>
<td>Effective density of states, valence band</td>
<td>Nv</td>
<td>1/m^3</td>
<td>Semiconductor material</td>
<td></td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>sigma</td>
<td>6.1*10^{-6}[S/m]</td>
<td>S/m</td>
<td>Basic</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>alpha</td>
<td>1.8*10^{-4}[1/K]</td>
<td>1/K</td>
<td>Basic</td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>Cp</td>
<td>235J/(kg*K)</td>
<td>J/(kg-K)</td>
<td>Basic</td>
</tr>
<tr>
<td>Density</td>
<td>rho</td>
<td>10500[kg/m^3]</td>
<td>kg/m^3</td>
<td>Basic</td>
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<tr>
<td>Thermal conductivity</td>
<td>k</td>
<td>429[W/(m*K)]</td>
<td>W/(m-K)</td>
<td>Basic</td>
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<tr>
<td>Young’s modulus</td>
<td>E</td>
<td>83e9[Pa]</td>
<td>Pa</td>
<td>Young’s modulus and Poisson’s ratio</td>
</tr>
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<td>1</td>
<td>Young’s modulus and Poisson’s ratio</td>
</tr>
</tbody>
</table>

Figure 2-7. Silver (Ag) material properties.

2.6 Conclusion

In this chapter, we investigated 1D organic solar cells with P3HT: PCBM only for electrical properties. Here we have shown the results for the acceptor and donor concentration as well as IV characteristics and PV characteristics. These observations lead us to consider 3D modeling of the organic solar cell using P3HT: PCBM as an active material and silver grids to demonstrate both the optical and electrical properties of an organic solar cell. The 1D modeling and analysis pave the path for studying the organic materials properties. It works with the electrical properties, which also needs to improve in order to make the solar cell more efficient.
CHAPTER 3

DESIGN AND ANALYSIS OF A STAND ALONE SOLAR PV SYSTEM WITH DC MICROGRID

3.1 Abstract

Recently DC microgrids have drawn more consideration because of the expanding use of direct current (DC) energy sources, energy storages and loads in power systems. Reliable operation of DC microgrids chiefly relies upon legal control strategy to adapt to transport voltage varieties because of sustainable source irregularity and load changes. This chapter proposes a design and analysis of a standalone solar PV system with DC microgrid. The proposed system comprises of a solar PV system with boost DC/DC converter, incremental conductance (IC), bi-directional DC/DC converter (BDC), and a DC-AC inverter to supply power to the AC loads and batteries. A DC-DC boost converter is interfaced with the proposed system to step up the PV array voltage and maintain a steady output voltage. The fluctuation nature of PV array makes them inadmissible for independent activity. To defeat the disadvantages an energy storage device is utilized as a part of the proposed framework to remunerate the vacillations and to keep up a smooth and ceaseless power stream in every working mode to loads. Bi-directional DC-DC converter (BDC) is equipped for changing energy between two DC buses. It can work as a boost converter which supplies power to the load when the PV system yield power is more prominent than the required load power. It likewise works in buck mode which charges from DC buses when yield power is not as much as the required load power. The proposed converter lessens the component losses and upsurges the efficiency of the complete system. The total system is designed and executed in MATLAB/SIMULINK environment.

3.2 Introduction

Recently, renewable energy sources have gained a lot of attraction because of high energy demand, changes in natural strategies, and the scattered populace around the world. The concern of the environmental changes is driving in significant variations in power generation and utilization designs. Different nations have set the objective of reducing 20% of greenhouse gas by 2020. These natural concerns have pulled in broad consideration to move towards more earth benevolent energy sources, for example, photovoltaics (PV)
system, wind turbines, and fuel cells. But these energy sources are directly dependent on the environment, for example, in PV systems, there are changes in the radiation of sunlight and temperature. The power produced from these sources fluctuates which effects inversely to the main power grid. The ideal approach to shield this issue is to move towards a more astute confined framework such as microgrid (MG). A microgrid can work in an islanded mode when there are blackouts for supplying power to local loads. A microgrid can likewise function as backup power when there is a lack of supply from the main grid. Point of common coupling (PCC) makes the connection between the microgrid and the main grid.

Additionally, both the PV systems and fuel cells produce direct current (DC) whereas the infrastructure of the exciting power generation system is based on alternating current (AC). While integrating these renewable energy systems with the present structure, this DC voltage must be changed to AC, utilizing converters which include additional transformation steps that lead to upsurge power losses, thus diminishing general framework proficiency. In fact, there are countless DC loads, for example, PCs, servers, mobiles, TVs and so on that require another step to convert this AC power to DC bringing on additional losses.

![Figure 3-1. A simple diagram of standalone solar PV system with Dc microgrid (Hasan, 2008).](image-url)
In this chapter, a standalone solar PV system with DC microgrid is presented. This proposed system consists of a PV system with incremental conductance (IC) MPPT, a DC-DC boost converter, bi-directional DC-DC converter and control circuits, DC-AC inverter and controller and a battery bank. The proposed converter decreases the component losses and upsurges the performance of the complete system. A simple diagram of the complete system is shown in figure 3-1, and this proposed system has been designed and implemented in Matlab/Simulink.

3.3 Modeling of Solar PV system

Solar PV module can be depicted as a course of action of solar cells in series and parallel encased in protective casing. Solar PV array made of strings of PV modules associated in parallel and each string comprises of modules associated in series to produce a remarkable amount of energy. A solar cell converts sunlight into electrical energy.

It can be defined as silicon (or other material) PN junction diode. A single solar cell produces a voltage of 0.5 to 0.8V contingent upon the technology with which it is made. Matlab/Simulink is where any part can be modeled utilizing its respective mathematical expressions.

A solar PV array can be modeled in three diverse ways as by utilizing Matlab/Simulink. One of the techniques is by modeling the part that utilizes numerical expressions. The following technique is to utilize the library block of Simpower frameworks, where a PV array can be modeled by gathering PV modules as indicated by the required power output. The third strategy is the utilization of the solar cell block from the simelectronics library. The distinction between this technique and the first is that in this strategy the solar cell block contains the numerical expression (Boujemaa and Rachid, 2014).

In our model, we have considered the solar array block from Simpower systems library which was established by NREL, USA. It is exclusively added to the sustainable power source segment of Simulink to encourage simple demonstration of sustainable power source frameworks which incorporate stand-alone, grid-connected and hybrid systems. The best element in this model is that we can show any size of PV array.
It encourages the user by permitting the determination of the panels from a considerable list of producers, and it gives us a chance to arrange the arrays in series and parallel as indicated by our model. The PV array block in Simpower frameworks is a five-parameter model which utilizes a current source driven by the sunlight in parallel with a diode, a shunt resistor, and series resistor are linked at the output.

![Diagram of solar cell equivalent circuit]

Figure 3-2. The equivalent circuit of a solar cell.

The diode I-V Characteristics $I_d$ is

\[ I_d = I_0 \left( \exp \left( \frac{V_d}{V_T} \right) - 1 \right) \]  \hspace{1cm} 3.1

\[ V_T = K_B \frac{T}{q} n_i N_{cell} \]  \hspace{1cm} 3.2

3.3.1 Modeling and simulation of the Boost converter

The simulink library has all the essential electronic components to show any electronic circuits. A boost converter has made utilizing a capacitor, an inductor, a diode and a switch that appears in figure 3-3. The operating system of a boost converter can be clarified in two modes. The main component of the boost converter is the switching transistor. It turns some portion of a circuit on and off rapidly. Normally the speed of the switching can be more than 1000 times each second.
Mode one (ON state): shown in figure 3-4, begins while the switch is in the ON state. In the ON state, the switch (MOSFET) behaves short-circuited, and the input current goes through the inductor and switch. Because of the law of induction, the inductor becomes charged, and the energy is being stored in it. The diode of the circuit acts as an open circuit in this stage.

Mode two (OFF state): appeared in figure 3-5, begins when the switch is turned OFF. The current crosses the
diode, inductor, resistor, the capacitor and then returns to the source. The inductor makes a high voltage spike as its attractive magnetic field collapses when the stream of current is in the OFF state. The energy stored in the inductor will begin to flow until the switch is in off state. At whatever point there is a voltage spike, the energy is pushed across the diode and stored in the capacitor. This procedure steps up the voltage, and the output voltage is acquired as the voltage of the capacitor.

![Diagram of DC to DC converter during the OFF state](image)

Figure 3-5. DC to DC converter during the OFF state

### 3.3.2 Incremental Conductance MPPT

The photovoltaic output voltage is fundamentally a component of atmospheric factors, for example, temperature and insolation. Incremental Conductance was planned considering a perception of P-V characteristic curve. This algorithm was produced to defeat some downside of the Perturb and Observe (P&O) algorithm. The impediment of the perturb and observe technique to track the peak power under the quick fluctuating climatic condition is overcome by IC technique. IC algorithm is the most ordinarily utilized technique since its outcomes can be figured rapidly, and its control is effortlessly executed. The IC can verify that the MPPT has come to the MPP and quit perturbing the working point.
Figure 3-6. Power vs. Voltage for IC Algorithm (Chafle, 2013).

The MPP can be computed by utilizing the connection between dI/dV and – I/V. When dI/dV is negative, MPPT lies on the right side of the recent position, and when positive the MPPT is on the left side (Putri, 2015). The equation of IC method is:

\[
\frac{dP}{dV} = \frac{d(V.I)}{dV} = I \frac{dV}{dV} + V \frac{dI}{dV} \quad \text{..................3.3}
\]

MPP has been reached when \(\frac{dP}{dV}=0\) and

\[
\frac{dI}{dV} = -\frac{I}{V}, \text{ at MPP}
\]

\[
\frac{dI}{dV} > -\frac{I}{V}, \text{ left side of MPP}
\]

\[
\frac{dI}{dV} < -\frac{I}{V}, \text{ right side of MPP}
\]

In the event that MPP lies on the right side, dI/dV< - I/V and after that the PV voltage has to be reduced to come to the MPP, and when MPP is on the left side, the PV voltage has to be increased to reach MPP. This algorithm has benefits over P&O in that it can decide when the MPPT has come to the MPP, whereas P&O oscillates around the MPP. Additionally, IC can track quickly increasing and decreasing irradiance conditions with higher precision than P&O (Safari, 2015). IC techniques can be utilized for finding the MPP, enhance the PV proficiency, lessen power loss as well as the system cost. The IC algorithm has shown in the figure 3-7.
3.3.3 PV Simulink model

Figure 3-8 is the Simulink representation of the PV system with DC-DC boost converter and IC MPPT.
3.4 Modeling of Bidirectional Buck-boost converter

Usually, the DC-DC converters for example buck and boost converters don't have bidirectional power stream capacity. This limitation is due to the existence of diodes in the structure that stop opposite current flow. Generally, an unidirectional DC-DC converter could be transformed into a bidirectional converter by supplanting the diodes with a governable switch in its construction.
**Boost Mode:** In this mode switch, Q2 and diode D1 enters conduction relying upon the duty cycle while the switch Q1 and diode D2 are off constantly.

At the point when Q2 is on, and D1, D2, Q1 are off, that can be short-circuited. Consequently, the lower voltage charges the inductor and the inductor current continues. Additionally, since the diode D1 is reversed biased in this mode and the Q1 is off, no current flows in Q1. When Q2 and Q1 both are off as well as D1, D2 can be open circuited. At this point in time, the current flowing through the inductor can't change and the polarity of the voltage across it reverses. In this manner, the diode D1 is forward one-sided and thus the
inductor current charges the yield capacitor C2 to a higher voltage. Subsequently, the yield voltage boosts up.

**Buck mode:** In this mode switch Q1 and diode D2 enters conduction relying upon the duty cycle while the switch Q2 and diode D1 are off constantly. At the point when Q2 is on, D2, Q1, and D1 are off, the inductor will be charged by the higher voltage battery, and the yield capacitor will also be charged. When D2 is on, and Q1, D1, Q2 are off, the inductor current can't change momentarily. As a result, it becomes discharged through diode D2. The voltage over the load is stepped down.

**Selection of Inductor and Capacitor:** A noteworthy design characteristic in a converter is the determination of the inductor. The overall converter operation depends on the design of the inductor. The primary concern is the size and weight of a powerful inductor, to the point that is may be the single heaviest part in the whole converter. To decrease the inductor weight and size, it is necessary to take small inductance value.

The least inductance value expected to guarantee the converter works in continuous conduction mode (CCM) is recognized as critical inductance(LCR) value. For the buck and boost converter, the critical inductance value is reliant on the steady-state duty cycle (D), switching period (TS) and load resistance (RL). The critical inductance for the boost converter is

\[ L_{cr,\text{boost}} = \frac{T_S R_L}{2} (1 - D)^2 \] ………………3.4

The critical inductance for the buck mode converter is

\[ L_{cr,\text{buck}} = \frac{(1-D)T_S V_0}{2I_0} \] …………………3.5

Additionally, the input capacitor, as well as output capacitor magnitude can be found from the capacitors ripple voltage,

\[ C_{in} = \frac{\Delta I_L}{8\Delta V_{in}} T_S \] …………………3.6
\[ C_{out} = \frac{V_0 D}{\Delta V_0 R_L} \frac{T_S}{\Delta V} \] …………………3.7

Where output ripple voltage is \( \Delta V_O \), inductor ripple current is \( \Delta I_L \).

3.5 Bidirectional Buck-boost converter Controller
The DC voltage is controlled by controlling the duty cycle by the bi-directional converter working in CCM. This controller keeps up a steady voltage at yield side for both boost and buck operation. The duty cycle of both switches creates by the controller. Two nested loops with the PI controller form this controller. Output voltage and inductor current are feedback signals to the PI controller.

![Bidirectional Buck-boost converter Controller in Simulink](image)

**Figure 3-12.** Bidirectional Buck-boost converter Controller in Simulink

3.6 **Modeling of the Inverter and Inverter controller**

An inverter consists of analog circuitry, a MOSFET driven incorporated circuit and a lowpass filter. The control circuit is involved in three fundamental blocks, the reference voltage, sine wave generator and carrier wave generator (carrier waves can be either sawtooth signals or triangular). At the point when these blocks are executed with comparators and other small simple circuitry, they control the PWM signals. The PWM signals are fed to the MOSFET drivers that perform level interpretation to drive four MOSFETs in an HBridge design. From here the signal is sent through a lowpass LC filter with the goal that the yield conveys a pure sine wave.

![Inverter controller design to control SPWM signal](image)

**Figure 3-13.** Inverter controller design to control SPWM signal
Figure 3-14. Sine and Triangle Wave Reference.

Figure 3-15. PWM control signal

Figure 3-13 shows the inverter controller design to control SPWM signal. Figure 3-14 demonstrates the signals that are passed into a comparator to achieve the PWM waveform. Figure 3-15 shows the generated PWM signal.

Producing a sine wave adjusted on zero volts needs a negative and positive voltage across the load, for the negative and positive parts of the wave, correspondingly. This can only be accomplished from a source using four MOSFET switches organized in an HBridge setup. An HBridge converter is a switching design made out of four switches in a plan that looks like an H. By controlling distinctive switches in the bridge, a positive, negative, or zero potential voltage can be put over a load. For getting a pure sine wave, the signal has been sent through a low pass filter.
In the figure 3-16, the design of the inverter has been shown, and the parameters used in the inverter are given in table 2.

### Table 2: Inverter parameters used in the simulation

<table>
<thead>
<tr>
<th>Parameters of the Inverter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dc grid Voltage</td>
<td>340VDC</td>
</tr>
<tr>
<td>DC bus capacitor</td>
<td>1000µF</td>
</tr>
<tr>
<td>Filter capacitors</td>
<td>1000µF</td>
</tr>
<tr>
<td>Filter Inductor</td>
<td>18mH</td>
</tr>
<tr>
<td>Frequency</td>
<td>50Hz</td>
</tr>
</tbody>
</table>

### 3.7 Modeling of Battery

The battery terminal voltage Vb and state of charge (SOC) are two significant parameters for the suggestion of the battery status. The battery model is given in MATLAB/Simulink. The parameters of the nickel metal hydride compose battery model are given as in Table III.

### Table 3: Battery parameters used in simulation

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>Rated Capacity</td>
<td>1150</td>
<td>Ah</td>
</tr>
<tr>
<td>SOC</td>
<td>Initial State-of-Charge</td>
<td>50</td>
<td>%</td>
</tr>
<tr>
<td>V</td>
<td>Nominal Voltage</td>
<td>160</td>
<td>V</td>
</tr>
</tbody>
</table>
3.8 Simulink representation of the complete system

![Simulink model of the complete system](image)

Figure 3-17. The complete model of the proposed system.

3.9 Simulation Results and Discussion

3.9.1 With the change of input irradiance

The PV array is provided with the temperature and irradiation data using a signal builder block in the Simulink. PV array of 20KW, IC MPPT has been used to track the highest power from the PV array, and a boost converter has been used to boost the voltage of the PV panel to its DC grid voltage of 340V. A bidirectional buck-boost converter has been implied to control the battery charging and discharge. A fixed DC load of 1KW and fixed AC load of 8KW, 500KVAR load, have been fed from this system. As this system is producing DC voltage, a DC to AC inverter is implied to power the AC loads of this system. Figure 3-18 shows the input irradiance for the system, and we consider an ambient temperature of 25°C for this simulation.
Figure 3-18. Input irradiation data using a signal builder block in Simulink

In figure 3-19 we can see that the power produced by the solar PV panel is different in time depending on the solar irradiation. When the irradiance is 1000 W/m², PV gives the highest power similar to its rating at almost 20KW. While decreasing the irradiance, the power output of the PV also decreases with time.

Figure 3-19. PV output power
As described above, in this system the DC grid voltage of 340V has been used. DC grid voltage and power supplied to DC load obtained in simulation as shown in Figure 3-20. As the PV array cannot produce less than the grid voltage, the DC-DC boost converter boosts the PV array voltage to 340V. From the figure, we can see that dc grid voltage is around 340V and the power supplied to the DC load is around 1000W though there are fluctuations when the irradiance suddenly drops down or goes up for both the DC grid voltage and power provided to the DC load.

The PV system gives the DC power, but we have the AC loads. To supply the power to the AC loads, we used a DC-AC inverter in our system. Figure 3-21. shows the AC voltage across the AC load, where there is also the sudden decrease and increase of voltage due to the sudden decline and rise of the irradiance.
Figure 3-20. DC grid voltage and power supplied to DC load
3.9.2 Battery charging and discharging

One of the main components of the system is the bi-directional buck/boost converter. The common dc link voltage (DC grid) is kept constant by the bi-directional flow of power between the battery and PV system. If the voltage increases above the predefined grid voltage value, i.e. 340V that means the PV system power is enough to feed the load and charge the battery and therefore, some current is sent to the battery to take down the voltage to 340V and in this case the bidirectional converter is operated in buck mode, stepping down the voltage from 340V to 160V (Battery Voltage). If the DC grid voltage goes down below 340V, this means the PV is not producing enough power to feed the load and therefore, some current is sent from the battery to the grid and in this case, the battery discharges and the bidirectional converter is operated in boost mode, i.e., boosting the voltage from 160 to 340V. Initially, we selected the battery state of charge (SOC) as 50%. With the input irradiance in the figure 3-18 the battery is in charging mode as the PV system is producing enough power to feed the loads as well as charge the battery, so the battery SOC is increasing at...
the time shown in figure 3-22. The bidirectional buck-boost converter is working as buck mode, the DC input voltage 340 V is buck to 160V by controller pulses.

Figure 3-22. Battery charging mode.

As the battery is charged and the bidirectional buck-boost converter is in buck mode, the battery current and power is negative shown in figure 3-23.
While giving the input irradiance below 700W/m² as shown in figure 3-24, the produced power from the PV system is not enough to feed the loads, so the bidirectional converter is working in boost mode to make the battery voltage 160V to 340V causing the battery to discharge as shown in the figure 3-24. When the input irradiance is more than 700W/m² the battery works in charging mode, as in the 3 and 4 minutes the irradiance is around 790W/m² and the battery charges during this period.
As we can see in figure 3-25, as the battery discharges the current is positive, when the battery goes to the charging mode the current becomes negative.
3.9.3 With the change of both input irradiance and temperature

For this case, we changed both the input irradiance and temperature. We consider input irradiance signal as figure 3-18 and change the temperature from -15°C to 45°C. With the change of the temperature, the PV power output decreases as shown in figure 3-26. With the increase of temperature, the PV output power is decreasing at a very high temperature. Even with a high irradiance the PV system cannot produce enough power to feed the loads, so the battery has to discharge to feed the load. We can see clearly from figure 3-27 that at 750W/m² irradiance when the temperature is below 30°C the PV power is enough to feed the loads but while the temperature is 35°C or more the PV power is not enough to feed the loads, so the power and current of the battery are positive.

Figure 3-26. PV output power is decreasing with the increase of temperature.
Figure 3-27. Battery power and current with the increasing temperature.
3.9.4 Energy output (PV array with MPPT)

The performance of a PV system, for the most part, relies upon the connection between the actual output and the ideal output of PV arrays. The actual output alludes to the actual estimated yield or in our case the simulated output of the installed PV array which incorporates losses and issues related with the PV array. The ideal output could be characterized as the expected yield that the PV array conveys under STC conditions. The equation of the performance ratio is given below. (Solaredge, 2016).

\[
PR = \frac{P(W)}{I(W/m^2) \cdot \frac{P_0}{1000 W/m^2}} \quad \text{Equation 3.8}
\]

\(I\) = Irradiance \((W/m^2)\)

\(P\) = Simulated power output \((W)\)

For the simplification we used the standard temperature 25°C and calculated the efficiency of the system from the ratio of the output of DC-DC boost converter and given rated input 20 KW with changing irradiance.

<table>
<thead>
<tr>
<th>Irradiance (W/m²)</th>
<th>Simulink result (KW)</th>
<th>Performance ratio% (P/P₀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>19.934</td>
<td>99.67</td>
</tr>
<tr>
<td>900</td>
<td>17.96</td>
<td>89.8</td>
</tr>
<tr>
<td>850</td>
<td>16.97</td>
<td>84.85</td>
</tr>
<tr>
<td>800</td>
<td>15.96</td>
<td>79.8</td>
</tr>
<tr>
<td>750</td>
<td>14.90</td>
<td>74.5</td>
</tr>
<tr>
<td>700</td>
<td>13.95</td>
<td>69.75</td>
</tr>
<tr>
<td>600</td>
<td>11.85</td>
<td>59.25</td>
</tr>
<tr>
<td>500</td>
<td>9.94</td>
<td>49.7</td>
</tr>
</tbody>
</table>

### Table 4: Performance ratio calculation with changing irradiance.

3.5 Conclusion

In this chapter, a unified method has been proposed to enhance the efficiency of solar PV systems effectively. At various irradiance and temperature, the system can utilize the battery for energy storage to retain the load voltage and current stability. As it’s a DC microgrid, the inverter effectively converts the DC power to AC to feed the whole 8KW 500VAR load effectively. Additionally, the bidirectional converter actively works to make the system always constant. The proposed system lessens the component losses and upsurges the efficiency of the complete system.
CHAPTER 4
FUZZY LOGIC MPPT CONTROLLER FOR PV NANOGRID AND STABILITY ANALYSIS OF THE SYSTEM

4.1 Abstract
This chapter presents an intelligent control technique using the fuzzy logic control to the MPPT control for effective operation under non-linear parameter variations for a nanogrid system and simulation results are obtained from MATLAB/SIMULINK. Additionally, a stability analysis of the DC microgrid system from the chapter is carried out in this chapter with a boost converter and bidirectional DC-DC converter to determine the Lyapunov function.

4.2 Introduction

PV system can't be demonstrated as a steady DC source since its output power relies upon the load current, temperature, and insolation. For the most part, MPPT is received to track the maximum power point in the PV framework. The productivity of MPPT relies upon both the MPPT control algorithm and the MPPT circuit. The MPPT control algorithm is generally connected in the DC-DC converter that is regularly utilized as the MPPT circuit.

From the seventies a remarkable number of MPPT control strategies have been proposed starting with basic (for example, voltage and current input based MPPT) to more enhanced power based MPPT (for instance, the P&O procedure and the incremental conductance strategy) methods. As of late intelligent based plans have been presented. In this chapter, intelligent based control strategy utilizing fuzzy logic control is related to an MPPT controller to enhance energy conversion efficiency. The real issue with the current solar energy MPPT technology is that the productivity of the PV system is still low and does not work on its best effectiveness relating to the nonlinear varieties (Takun, 2011).

This chapter presents an intelligent control technique using the fuzzy logic control to the MPPT
control for effective operation under non-linear parameter variations. The simulation is implemented in MATLAB and Simulink.

4.3 MPPT using Fuzzy Logic Control (FLC)

MPPT utilizing Fuzzy Logic Control increases a few points of interest for better execution and simple design. Also, this strategy does not require the information of the correct model of the framework. The primary parts of FLC are fuzzification, run base, inference, and defuzzification, appeared in Figure 4.1. FLC is executed to get the MPP operation voltage point speedier with less overshoot and furthermore can limit the voltage vacillation after MPP has been perceived. The control objective is to track maximum power that will lead to enhance the efficiency of the total PV system.

In the fuzzification phase, numerical input factors are ascertained or changed over into linguistic variables based on a subset called membership function. To decipher the value of change in voltage and power, fuzzy input "change in power" and "change in voltage" is composed of seven factors called NM (Negative Medium), NB (Negative Big), PB (Positive Big), PM (Positive Medium), NS (Negative Small), PS (Positive Small), ZE (Zero). Change in voltage and power are the input variables in the proposed framework, and the yield from the FLC is the change in the duty cycle. The membership functions of each variable are shown in figures 4.2 to 4.4.
Figure 4-2. The input of FLC change in voltage

Figure 4-3. The input of FLC change in power.

Figure 4-4. The output of the FLC as a change in duty cycle.

The fuzzy rule algorithm gathers an arrangement of fuzzy control rules in a particular order. These
principles are utilized to control the system to meet the execution prerequisite, and they are planned from the master learning of the system under control. The fuzzy inference of the FLC depends on the Mamdani's' strategy that is related with the maximum, minimum composition (Garg, 2015).

<table>
<thead>
<tr>
<th>Dp</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>PB</td>
<td>PM</td>
<td>PS</td>
<td>NS</td>
<td>NS</td>
<td>NM</td>
<td>NB</td>
</tr>
<tr>
<td>NM</td>
<td>PM</td>
<td>PS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NM</td>
<td>NM</td>
</tr>
<tr>
<td>NS</td>
<td>PS</td>
<td>PS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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</tr>
<tr>
<td>ZE</td>
<td>NS</td>
<td>NS</td>
<td>PS</td>
<td>ZE</td>
<td>ZE</td>
<td>NS</td>
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<td>PS</td>
<td>NS</td>
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<td>NS</td>
<td>PS</td>
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<td>PS</td>
<td>PS</td>
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</tr>
<tr>
<td>PB</td>
<td>NB</td>
<td>NB</td>
<td>NM</td>
<td>PS</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
</tr>
</tbody>
</table>

The input for the defuzzification procedure is a fuzzy set, and the output is a solitary number that must be connected to the system. Different defuzzification strategies are utilized these days, but the most basic strategy used is the centroid of zone and bisector of the zone. In the proposed system, centroid defuzzification strategy is utilized for defuzzification.

4.4 Characteristics of the PV module

The specifications of the PV module used in this simulation are shown in Table 5.

<table>
<thead>
<tr>
<th></th>
<th>Maximum power (P_MPP)</th>
<th>Current at Pmpp (I_MPP)</th>
<th>The voltage at Pmpp (V_MPP)</th>
<th>Open circuit Voltage (V_OC)</th>
<th>Short circuit current (I_SC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>129.94(W)</td>
<td>4.45(A)</td>
<td>29.2 (V)</td>
<td>36.6 (V)</td>
<td>4.82(A)</td>
</tr>
</tbody>
</table>

The V-I and P-V characteristics of the module are attained for a steady temperature of 25°C and at 1000 W/m2 irradiance are shown in Figure 4-5 and 4-6 individually.
4.5 Simulation Results

The output power of the PV module and converter with fuzzy logic MPPT strategies are obtained in MATLAB/Simulink at an irradiance of 1000 W/m² and temperature of 25°C. From the simulation, we got the PV array output power of 129.9W, output voltage of 29.23V and current of 4.445A. In figure 4-7-4.9 the outputs of PV array are given.
4.6 Stability Analysis

For the stability analysis of our system in chapter three, we consider the two controllers, DC-DC boost controller and bidirectional DC-DC buck-boost converter.
The PV module is displayed by a current source $I_{ph}$ associated in parallel with a diode and with a shunt resistor $R_p=301.8149$ and $i_D$ the current output of PV module (Sun, 2017).

$$i_D = I_{ph} - i_{D1} - i_{R_p}$$
$$i_{D1} = I_0(e^{av1} - 1)$$
$$a = \frac{q}{nkr} = 11622.0959 \text{ (at 25°C)}$$

We consider two controls in the model. The control signals are duty cycles of the converters. $S_1$ controls the power output of the PV; $S_2$ controls the DC bus voltage. Utilizing Kirchhoff's laws, the dynamic model of the system can be composed as

$$L_1 \frac{d i_1}{dt} = v_1 - v_2 (1 - s_1)$$
$$C_1 \frac{dv_1}{dt} = i_D - i_1 = I_{ph} - I_0(e^{av1} - 1) - \frac{v_1}{R_p} - i_1$$
$$L_2 \frac{d i_2}{dt} = E - i_2 r - v_2 s_2$$
$$C_2 \frac{dv_2}{dt} = i_1(1 - s_1) + i_2 s_2 - \frac{v_2}{R_1}$$

with the constraints: $v_2 > 0, i_1 > 0$.

Let $x^T = [x_1, x_2, x_3, x_4] = [i_1, v_1, i_2, v_2]$ and the system can be rewritten as state space model
\[
\begin{align*}
\dot{x}_1 &= \frac{1}{L_1} [x_2 - x_4(1 - s_1)] \\
\dot{x}_2 &= \frac{1}{C_1} \left[ I_{ph} - I_0 \left( e^{ax_2} - 1 \right) - \frac{x_2}{R_p} - x_1 \right] \\
\dot{x}_3 &= \frac{1}{L_2} \left[ E - r x_3 - x_4 s_2 \right] \\
\dot{x}_4 &= \frac{1}{C_2} \left[ -\frac{x_4}{R_1} + x_1 (1 - s_1) + x_3 s_2 \right]
\end{align*}
\]

with the constraints: \( x_1 > 0, x_4 > 0 \)

Moving the equilibrium points of the system to the origin and the system without control which is \( s=0 \) is globally asymptotically stable (Sun, 2017).

\[
\begin{bmatrix}
1 \\
\frac{1}{L_1} [x_2 - x_4] \\
-\frac{x_1}{C_1} - \frac{x_2}{R_p} - I_0 e^{ax_2} (e^{ax_2} - 1) \\
\frac{1}{L_2} [-r x_3 - x_4] \\
\frac{1}{C_2} [x_1 - \frac{x_4}{R_1}]
\end{bmatrix}
\]

With the Lyapunov function

\[
V(x) = \frac{1}{2} L_1 x_1^2 + \frac{1}{2} C_1 x_2^2 + \frac{1}{2} L_2 x_3^2 + \frac{1}{2} C_2 x_4^2
\]

\[
\dot{V}(x) = L_1 x_1 \dot{x}_1 + C_1 x_2 \dot{x}_2 + L_2 x_3 \dot{x}_3 + C_2 x_4 \dot{x}_4
\]

Considering only the boost converter and replacing the values of parameters from chapter 3 and \( s_1 \) as zero we get,

\[
\begin{align*}
\dot{x}_1 &= 20000 \times [x_2 - x_4] \\
\dot{x}_2 &= \frac{1}{1000 \times 10^{-6}} \left[ 8.5795 - 2.0381 \times 10^{-10} (e^{11622.095x_2} - 1) - \frac{x_2}{301.81} - x_1 \right]
\end{align*}
\]

Computing a quadratic Lyapunov function \( V(x) \) for the system

\[
V_1 = 0.1836 \times x_1^2 + 1.506e - 18 \times x_1 \times x_2 + 0.3134 \times x_2^2
\]

Considering only the bidirectional buck-boost converter and replacing the values of parameters from chapter 3 and \( s_2 \) as zero we get,
\[ \dot{x}_3 = \frac{1}{5 \times 10^{-5}} \left[ 160 - 0.0039 \times x_3 \right] \]
\[ \dot{x}_4 = \frac{1}{1000 \times 10^{-6}} \left[ -\frac{x_4}{0.0001} \right] \]

Computing a quadratic Lyapunov function \( V(x) \) for the system

\[ V_2 = 0.2476 \times x_3^2 + 5.654e - 7 \times x_3 \times x_4 + 272.3x_4^2 \]

4.7 Conclusion

An intelligent control technique using fuzzy logic control to the MPPT control for effective operation under non-linear parameters variations for a nanogrid system and simulation results are obtained from MATLAB/SIMULINK. The results are in accordance with the PV panel outputs. Additionally, a stability analysis of the DC microgrid system from the chapter three is carried out in this chapter with boost converter and bidirectional DC-DC converter and proposed the Lyapunov function of the system.
5.1 Conclusion

In this thesis, we have explored different aspects of the solar renewable energy source. Firstly, we have studied the more environmentally friendly solar cells which are an organic solar cell. Later, we have investigated the possibilities of the DC microgrid system and its viability. Additionally, we integrated a fuzzy logic MPPT controller to a small nanogrid DC system to make the PV system more efficient. We concluded doing the stability analysis of the DC microgrid system with the two controllers.

In chapter 2, we have investigated 1D organic solar cell for P3HT: PCBM material. We observed the results of this 1D solar cell for its electrical properties which lead us to consider 3D modeling of the organic solar cell using P3HT: PCBM as an active material and silver grids to demonstrate both the optical and electrical properties of an organic solar cell. It works with the electrical properties, which also needs to improve to make the solar cell more efficient.

In chapter 3, a complete design and analysis have been proposed to effectively enhance the power conversion efficiency of a standalone solar PV system with DC microgrid. PV array of 20KW, IC MPPT, a boost converter and a bidirectional buck-boost converter have been implied to control the battery charging and discharging. The proposed converter decreases the component losses and upsurges the performance of the complete system. A fixed DC load of 1KW and fixed AC load of 8KW, 500KVAR load, have been fed from this system.

In Chapter 4, a study of the fuzzy logic MPPT controller modeling has been carried out for a small nanogrid PV system. The simulation results show that FLC can effectively track the maximum power of the PV system. Later we did a stability analysis of the DC microgrid of chapter three for the boost controller and bidirectional buck-boost controller and figured out the space state equations and Lyapunov function using sum-of-squares optimization.
5.2 Future Work

In chapter 2, the 3D design of an organic solar cell (OSC) has been presented which should be further enhanced by doing both optical and electrical modeling and analysis. Also, novel designs of the organic solar cells can be analyzed, and from trial and error, efficient models of organic solar cells could be used to improve the efficiency of the OSCs. Additionally, COMSOL MULTIPHYSICS has to be analyzed further for designing and simulating different designs of OSCs with various organic materials. In chapter 4, a fuzzy logic MPPT controller has been proposed in a PV nanogrid system; this controller can be implemented for a more significant system like the DC microgrid system in chapter 3 and the results have to be analyzed. Furthermore, FLC can be compared with the incremental conductance MPPT in chapter 3. In this chapter, we proposed the state space model for the two controllers of the DC microgrid system in chapter 3 and ignored the controller for the load voltage. But all the three controllers of the DC microgrid system can be considered for the stability analysis of the whole system.
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