Design and Control of DC Microgrid with Hybrid Storage System

Capstone Report

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Abstract:

This article conducts a comprehensive analysis of the design and simulation of a direct current (DC) microgrid system that incorporates a hybrid energy storage system—a technological advancement that merges the strengths of a supercapacitor (SC) and a battery energy storage system (BESS). The primary objective of this research is to resolve the issues related to intermittent power supply that arise from photovoltaic systems, which are renewable energy sources. Additionally, the study aims to establish a dependable and consistent power supply for DC applications by eliminating the need for intricate AC conversion components. The simulation results illustrate that the system effectively sustains a consistent direct current (DC) bus voltage in spite of the rapid fluctuations in solar irradiance. The BESS is efficiently employed to provide continuous energy supply, whereas the SC promptly reacts to sudden surges in demand, thereby improving the overall stability as well as efficiency of the system.

Contents

Chapter 1

Introduction

A DC microgrid is one of the reliable solutions in delivering power from renewable energy sources [1], [2]. A mechanism known as a DC microgrid functionsthrough the utilization of direct current (DC), which varies from alternating current (AC) and is primarily employed in supplying localized electrical power torelatively modest loads [3], [4]. Frequently, direct current microgrids are used invarious applications, ranging from non-connected systems that harness renewableresources to charging points tailored for electric vehicles and even data centers [5],[3]. DC microgrids are incorporated into the framework of renewable energyinfrastructure for their capability to assimilate various DC power generation technologies such as wind turbines and solar panels [6]. These microgrids' flexibility and adaptive nature make them a prevalent method within the industry. Including a DC microgrid excludes the need for converting between DC and AC [7], which significantly improves the system's overall efficiency levels [8], [9].

Within the framework of a DC-based microgrid that seeks to bring an alternative, ecologically-sound energy sources into existence, any output produced by said source takes the form of direct current — this type of electrical power is then subsequently channeled directly into the existing DC network bus system belonging to said microgrid establishment [10], [11]. Usually linked to an energy storage system like batteries or supercapacitors assists in accumulating surplus energy produced by renewable sources and releases it when requisite [5], [9]. The DC microgrid is typically equipped with DC-DC converters, which enable the integration of vari- ous other DC loads like lighting systems, electric vehicle chargers, and household appliances [1], [12].

It has the capacity to step up or step down voltage levels as required based on the needs of these specific loads [5], [10]. DC Microgrid equipped with a hybrid energy storage system is a reliable technical solution for managing and transferring electric power from eco-friendly renewable energy sources [13], [14]. Hybrid energy storage systems include supercapacity energy storage systems (SESS) [15] combined with battery energy storage (BES) systems [16],[15].

Former is one of the best choices for regulating the transient power of DC microgrids be- cause of its high-power density and reliability [5], [17]. The BES system plays a ‘reserve’ role in our system, providing sufficient power when SESS energy is not enough for the consumer [18], [19]. The utilization of a supercapacitor-based energy storage system is highly advantageous for the purpose of power smoothing due to its rapid charge and discharge capabilities.

Chapter 2

System architecture

The designed DC microgrid architecture consists of a Photovoltaic (PV) system enhanced by a hybrid energy storage arrangement that incorporates both a Battery Energy Storage System (BESS) and a Supercapacitor (SC). As can be seen from Figure 2.1, The PV system connects to the direct current (DC) bus through a boost converter and is controlled by a Perturb & Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm. The BESS and SC are connected in parallel to the DC bus using separate DC-DC bidirectional converters. In this project, the DC bus provides power to a constant DC load. Unlike the other architecture, it does not connect to the utility through a single-phase inverter. Instead, it strictly follows a DC framework. This model includes a 2kW PV system containing Corby NN17 plates.

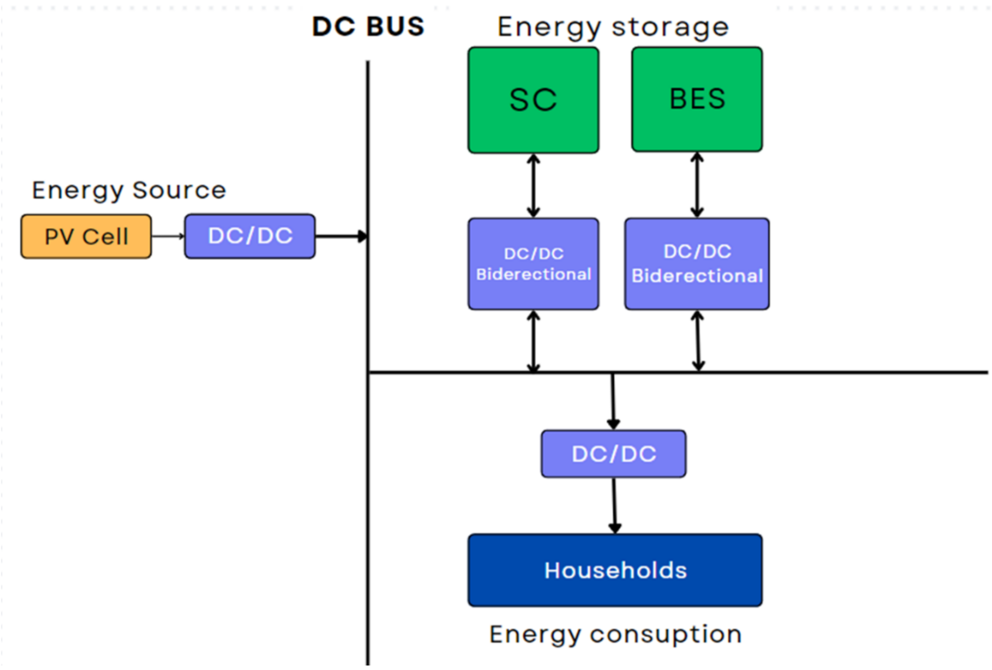

Figure 2.1: Diagram of DC Microgrid

Control systems are specifically intended to regulate energy flow from storage devices to the load. The bidirectional converter control is carefully adjusted to effectively manage the load's power needs, taking into account the fluctuating levels of power output from the PV system. The PV system employs an array arrangement consisting of an ideal number of module strings that align with the microgrid's power needs. The simulation utilizes a model that closely resembles the industry-standard requirements.

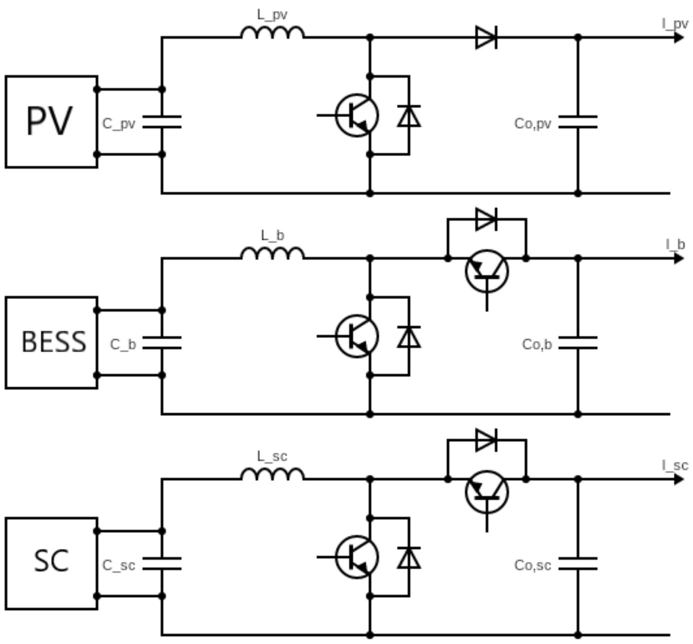

Figure 2.2: Circuit schematic of DC Microgrid

The P&O MPPT algorithm improves the efficiency of power extraction from the PV array by assuming that the derivative of power with respect to voltage (dP/dV) is zero at the maximum power point (MPP). From Figure 2.3, the method modifies the operating point of the PV array by comparing the current power with the power from the previous step, increasing or decreasing the voltage reference until the maximum power point is found and maintained.

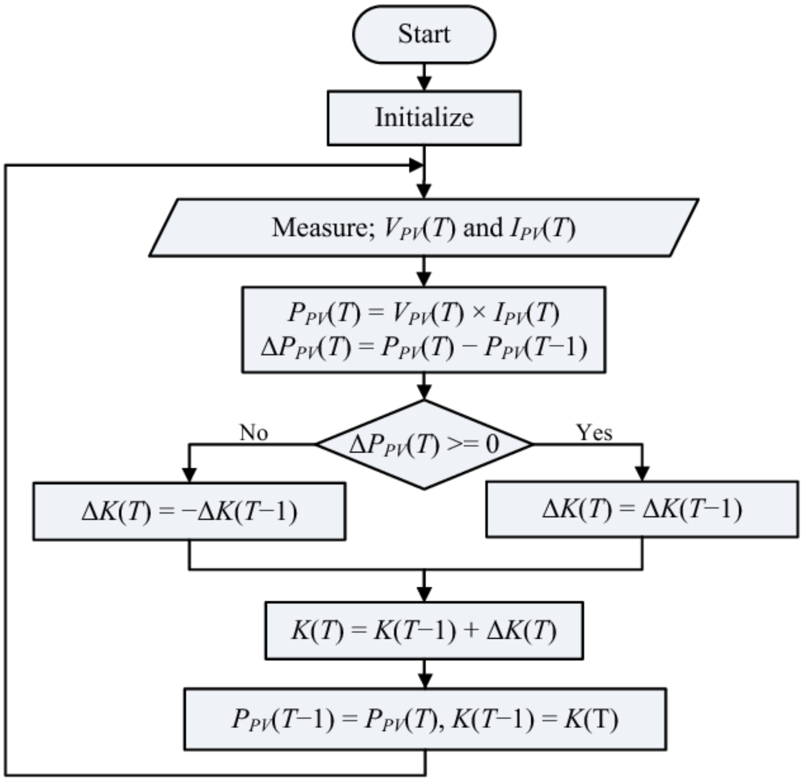

Figure 2.3: P&O MPPT algorithm logic

The energy storage mechanism utilizes the high energy density of Lithium-ion batteries, which are well-suited for providing sustained energy, in combination with a Supercapacitor. The SC is particularly effective at delivering high power when there are unexpected load or PV generation fluctuations. Both storage systems are simulated using the extensive libraries provided in MATLAB/Simulink, allowing for an accurate representation of their behavior in the microgrid setting. The specifications for both the BESS and the SC are meticulously organized in tables to represent their function accurately within the system design. Figure 2.4 demonstrates their capacity, voltage range, and other relevant features that align with their modelled performance.

Component	Parameter	Value
PV module	Maximum Power	100 W
DC bus	Voltage	400 V
DC load	Resistance	180 Ohm
PI Controllers	Battery	$K_p = 0.1, K_i = 0.1$
	Supercapacitor	$K_p = 0.1, K_i = 0.1$
	Outer Voltage Loop	$K_p = 0.015, K_i = 0.06$
Battery	Rated Voltage	195 V
	Capacity	26 Ah
Supercapacitor	Rated Voltage	210 V
	Capacitance	46 F

Figure 2.4: Component values

Chapter 3

Simulation Setup and Methodology

Using MATLAB Simulink, a simulation environment was developed to represent a DC microgrid system comprised of an SC, a PV array, and a BESS, all of which were connected to a 400V DC bus, as shown in Figure 3.1. The PV array, designed to replicate a 2 kW system, was set up with ten module strings arranged in parallel with two strings. This setup enabled an accurate representation of a moderately sized photovoltaic (PV) installation, which is frequently encountered in decentralized power systems.

In order to simulate conditions varying from overcast to peak sunlight, solar irradiance was established as a dynamic input variable that affected the power output of the PV array. The irradiance was decreased by 25% in each time interval. The P&O algorithm's efficiency was measured by monitoring the PV array's power-voltage (P-V) curve.

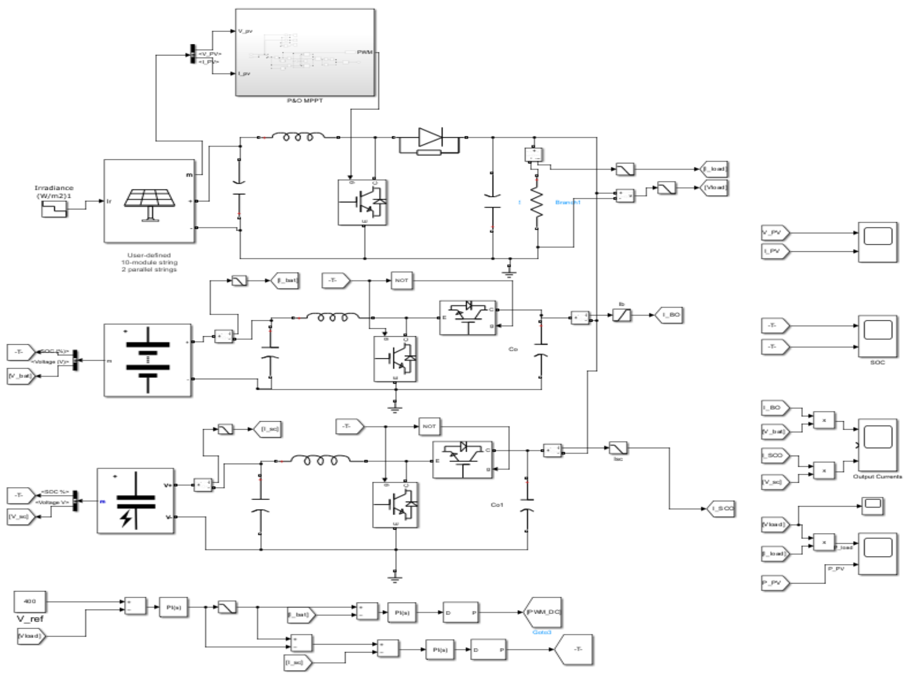

Figure 3.1: Microgrid Simulation model

The core of this system consists of a twin-cascaded Proportional-Integral (PI) controller that precisely manages the voltage and current provided to the DC bus. As shown in Figure 3.2, the voltage regulation loop is responsible for maintaining a consistent bus voltage, which is essential for the stable functioning of the microgrid. The system functions by establishing a fixed voltage reference level that it endeavours to uphold, adjusting to variations in load or generation. The existing regulatory loop operates in conjunction with the voltage regulation loop, producing a current reference that is affected by the load demand and the electricity available from the photovoltaic system.

The current reference is divided into two paths to effectively manage the energy flow from the BESS and the SC: one is allocated for consistent, long-term load demands, while the other is utilized for swift, transient fluctuations. The BESS, known for its superior energy density, is responsible for fulfilling the steady load demands. The PI controller is linked to this channel and regulates it by modifying the duty cycle of the bi-directional converter. This adjustment is based on the filtered current reference, representing the average load demand. The SC is utilized for temporary load requirements. The system's controller analyzes the high-frequency elements of the current reference and promptly responds to abrupt changes in power requirements. This guarantees that the microgrid can promptly adapt to fluctuations, preserving a consistent power supply to the DC demand while also maximizing the utilization of the storage components for durability and effectiveness.

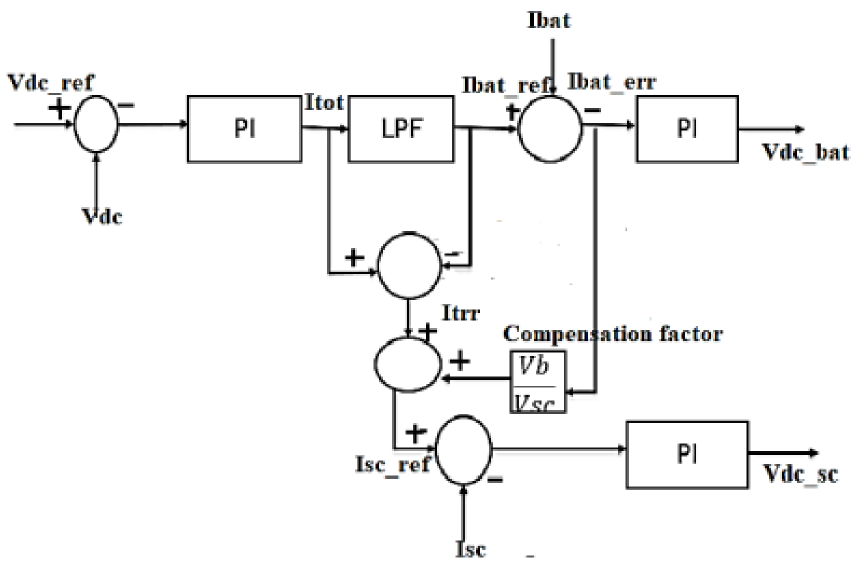

Figure 3.2: PI Control strategy

In order to accurately simulate the power usage patterns of a typical residential or commercial unit functioning on the microgrid, a static 180-ohm resistor connected to the DC bus was utilized to represent the load.

$$I_{outmax} = \frac{P}{V_{out}}$$

$$\Delta I_L = 0.01 * I_{outmax} * \left(\frac{V_{out}}{V_{in}}\right)$$

$$\Delta V_{out} = 0.01 * V_{out}$$

$$L = \frac{V_{in}(V_{out} - V_{in})}{\Delta I_L * f_s * V_{out}}$$

$$C = \frac{I_{outmax} * (1 - \left(\frac{V_{in}}{V_{out}}\right))}{f_s * \Delta V_{out}}$$

$$R = \frac{V_{out}}{I_{outmax}}$$

$$d = \frac{V_{out} - V_{in}}{V_{out}}$$

Figure 3.3: Component value formulas

This simulation methodology was designed to provide a practical foundation for evaluating the effectiveness of the proposed DC microgrid system in different operating situations. The arrangement allowed for precise control over the simulation parameters, resulting in a thorough understanding of the system's behaviour. This enabled the optimization and validation of the suggested architecture.

Chapter 4

Results and Discussions

To The simulation results, illustrated in Figures 4.1, 4.2, and 4.3, offer a measurable evaluation of the power distribution within the DC microgrid. The voltage and current characteristics of the photovoltaic (PV) system are illustrated in Figure 4.1. Despite fluctuations in irradiance, the PV voltage (V_PV) maintains a consistent value of around 200V for the duration of the simulation, demonstrating that the MPPT control strategy is functioning optimally. In the same way, the photovoltaic current (I_PV) exhibits a step-by-step decrease, corresponding to the intended reductions in irradiance throughout the simulation duration. At the starting point, the current remains approximately 10A, equivalent to the PV system's 2 kW power output during periods of maximum irradiance. The current decrease, in tandem with the reductions in irradiance, reflects the reduction in the ability to produce power.

The DC bus voltage, illustrated in Figure 4.2, demonstrates remarkable stability throughout the simulation period, consistently remaining at approximately 400V. The stable voltage level observed on the DC interface indicates that the energy storage system has effectively counterbalanced the declining PV output by maintaining a suitable voltage level, regardless of the decreasing PV power.

Figure 4.3 presents a comparative analysis of the PV power and consumption of DC loads. In the beginning, the photovoltaic power surpasses the peak demand of 1 kW, which allows the allocation of the excess energy to the energy storage system. When the photovoltaic (PV) power output decreases, the energy storage system releases energy to make up the difference and ensure that the demand power requirement is met. The graph illustrates a short transitional period during which the dynamics of the storage system are modified, after which the system returns to a state of equilibrium.

Figure 4.4 illustrates how the BESS and SC power outputs in our DC microgrid project highlight their pivotal functions in energy management. Long-term energy provision is exemplified by the BESS power output, which initially peaks to sustain the load and then decreases further as PV input decreases. The SC, on the other hand, responds to short-term fluctuations by maintaining system stability through its rapid charge and discharge cycles. This data exchange provides empirical support for our hypothesis that implementing a hybrid storage system for microgrids improves their resilience by guaranteeing consistent energy provision in the face of fluctuating renewable energy supplies.

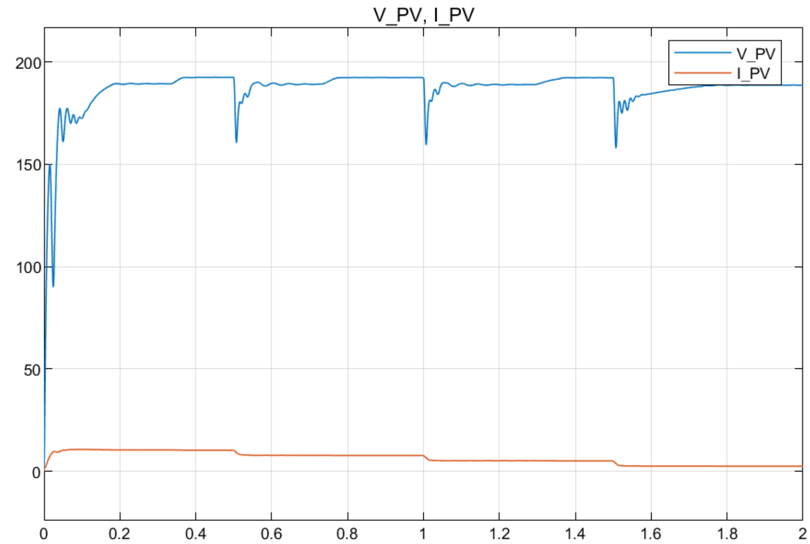

Figure 4.1: PV voltage (V), PV current (A).

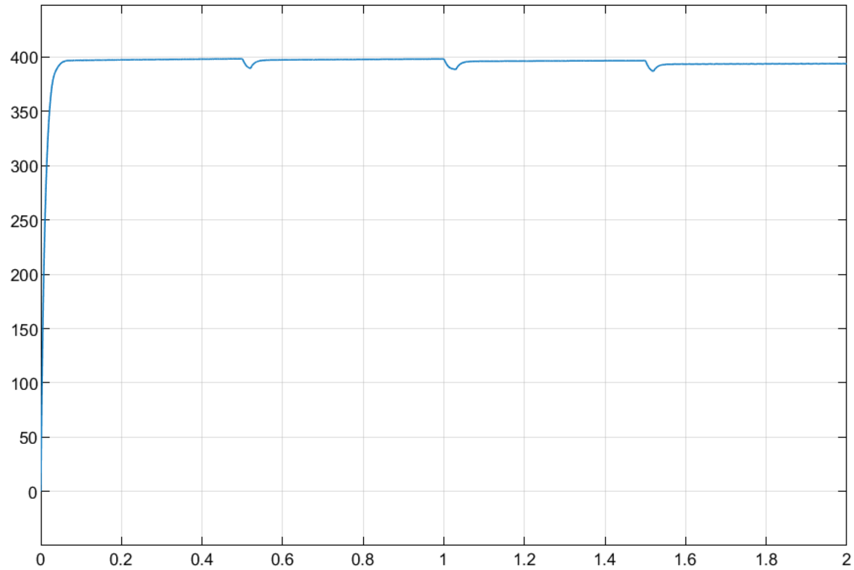

Figure 4.2: DC bus voltage (V).

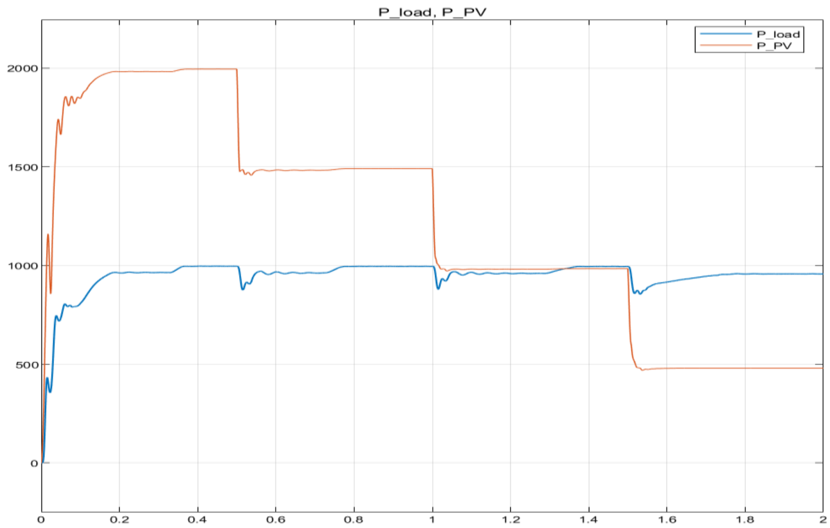

Figure 4.3: PV power(W), DC load power(W).

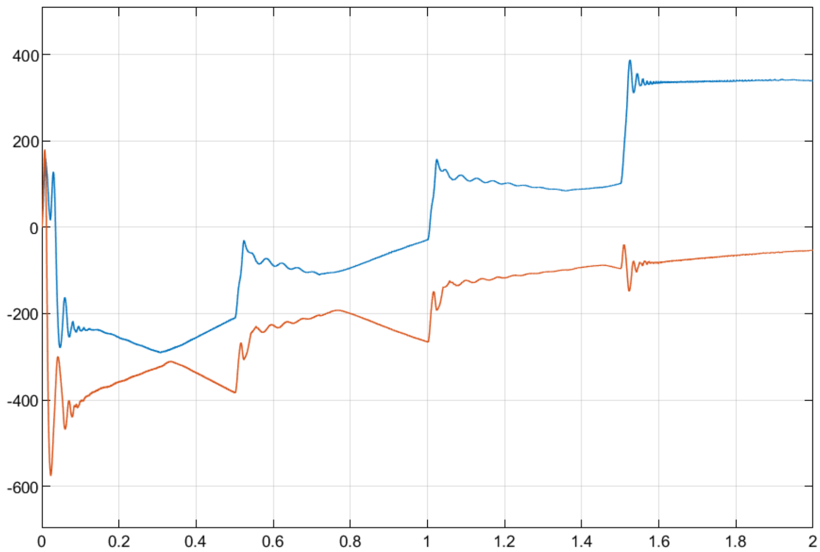

Figure 4.4: BESS power(W), SC power(W).

Chapter 5

Conclusion

The DC microgrid, with PV as a main energy source and hybrid battery system, is designed to have a stable 400 Volts output. A suitable PI controller was designed to obtain stable output while the PV module Perturb and Observe (P&O) algorithm was implemented for maximum power point (MPP) tracking. Independent converters were designed for each energy block. As a result, it was found that the system maintains a constant load power requirement through efficient energy management and demonstrates stability and reliability even when the solar irradiance is decreased. Nevertheless, this study provides opportunities for additional advancements and investigations. Further iterations may investigate the effects of temperature on system performance, considering the substantial influence that these variables can have on both photovoltaic output and storage efficiency. The simulated DC microgrid with HESS highlights the potential of such systems in real-world applications where renewable energy sources are subject to environmental variabilities and uncertainties.

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