Modelling and analysis of multi-input multi-output dc-dc converter topology for renewable energy integration.

MODELLING AND ANALYSIS OF MULTI-INPUT MULTI-OUTPUT DC-DC CONVERTER TOPOLOGY FOR RENEWABLE ENERGY INTEGRATION

By

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Submitted as a Partial Requirement for the

Master's degree in engineering (MEng): Electrical Engineering

Field of Specialization: Power Electronics

In the Department of Electrical Engineering

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April, 2024

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I hereby declare that the dissertation submitted for the degree MEng at Tshwane University of Technology is my own original work and has not previously been submitted to any other institution of higher education. I further declare that all sources cited or quoted are indicated and acknowledged by means of a comprehensive list of references.

MTHOBISI W NTULI

DEDICATION

Dedicated to my late friend ***Smanga Steven Nkosi***, I'll always love you.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude and appreciation to my supervisors Dr AF Nnachi and Dr CG Richards, for their guidance, patience, and support during this research period. Their technical skills, human qualities and persistent motivation have been a model to me.

I also would like to thank Tshwane University of Technology for the opportunity to do my research with the institution and for providing all the necessary tools I required to conduct my research.

Furthermore, I extend a token of appreciation to my friends who were always there by my side and supporting me all the way. Busa Bam Hogana, Colani Ayanda Sganji Mndawe, Nomsa Ntsango, Sindiswa Nkosi, Prudence Zwane-Phoswa, Nomistake Manzini, Simphiwe Mncube, Jabulani Mahlangu, Bongani Maziya and my late friend Smanga Steven Nkosi, I'll forever be grateful for your loyalty and encouragements.

Last, but not least, I would like to thank my parents Mr. MP Ntuli and Mrs. ZV Ntuli and my siblings Dr Themba Ntuli, Sibusiso Ntuli and Thabile Ntuli for their support, prayers, and good wishes. Ngiyabonga boGodide, Mphemba, Ndlela kaSompisi!

ABSTRACT

Providing continuous and reliable power is the goal of every energy utility. However, the South African Energy utility has been unable to meet consumer demand resulting in load shedding. These power cuts are attributed to the aging infrastructure of the power utility and its dependence on fossil fuels to generate power. The power cuts have threatened the economy of the country and the stability of the national grid. This prompted the South African Government to draw plans to mitigate this threat. The plan is to introduce large scales of renewable energy sources into the energy mix with the key contributor being solar PV generators.

Photovoltaic power generators have been studied extensively and have proven to be a suitable candidate for the replacement of coal-fired power stations due to the many advantages these systems have which include zero carbon emissions, noise-free, no signs of minimal degradation even after prolonged usage, and do not contain any moving parts thus requiring very little maintenance. However, these systems have limitations especially when used as stand-alone systems due to the inherent intermittent nature of PV generators. This feature results in varying output power and excessive frequency deviations which affect the normal operation of the power plant. This problem may be averted by hybridizing PV generators with alternative energy sources such as fuel cells, wind generators and battery storage systems.

Recently, fuel cells have received attention as a promising power source for hybridization with PV systems to improve overall system quality and sustainability. This research aims to propose a Multi-input Multi-out DC-DC Converter for hybrid system topology and control to provide a reliable, controllable, and sustainable power supply. This Multi-input Multi-output converter is intended to overcome the problems of intermittent power, which is inherent to PV systems, and to

propose an eco-friendly alternative to fossil fuel power generators. To achieve this, Mathematical descriptions obtained from past studies will be employed for the mathematical models of each of the system components. Computer Software MATLAB/SIMULINK will be utilized to model and simulate the converter for hybrid systems and the control strategy. MATLAB will be used to analyze the total system performance.

Keywords: Multi-input, Multi-output, Fuel cells, Photovoltaic generators, Boost-Converter, Buck-converter MATLAB/SIMULINK

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GLOSSARY

CM	Common mode
CSC	Current source converter
DG	Distributed generation
DSP	Digital signal processor
FLC	Fuzzy Logic Controller
GTO	Gate turn-off thyristor
HEV	Hybrid electric vehicles
HVDC	High voltage direct current
HV-IGBT	High voltage insulated gate bipolar transistor
I_{avg}	Average current
IGBT	Insulated gate bipolar transistor
IGCT	Integrated-gate-commutated thyristor
I_{rms}	RMS current
MIMO	Multi-input Multi-output Converter
MLC	Multilevel converter
MOSFET	Metal oxide semiconductor field-effect transistor

NPT-IGBT	Non-punch through insulated bipolar transistor
PI	Proportional integral
PS	Phase shifted
PT-IGBT	Punch-through insulated bipolar transistor
PV	Photovoltaic
PWM	Pulse width modulation
RMS	Root-mean-square value
SHE	Selective harmonic elimination
SPWM	Sinusoidal pulse width modulation
SVM	Space vector modulation
SVPWM	Space vector pulse width modulation
THD	Total harmonic distortion
V_{DC}	DC-bus voltage
VSC	Voltage source converter
VSC BTB	Voltage source converter Back-to-Back
VSI	Voltage Source inverter

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CHAPTER 1

1.1. INTRODUCTION

In the later months of 2007, South Africa experienced its first series of what would eventually be ongoing widespread rolling-blackouts as the state-owned power utility fell behind consumer demand. These widespread blackouts have threatened the stability of the South African economy. South African lawmakers have attributed these rolling-blackouts to insufficient generation capacity [1] [2]. Power Generation in South Africa is largely sourced from coal-fired power stations, which contributes an installed capacity of 38GW [3]. In addition to the ongoing rolling blackouts, the energy sector contributes close to 80% of the country's total carbon emissions and 50% of the emission come from electricity generation and liquid fuel production [4].

To bring stability to the National Transmission Grid and reduce emissions, the South African Government drafted the National Development Plan (NDP) and the Integrated Resource Plan (IRP) 2019. In these documents the Government outlined plans to reduce the amount of power from coal fired power stations and to introduce large scales of renewable energy sources in the form of Solar-PV and Wind Power into the energy mix. The South African government plans to introduce a total of 6522MW from renewable energy sources of which 6422MW will come from the Renewable Energy Independent Power Producer Program (REIPPP) and 100MW will be from the state-owned power utility's (Eskom) own build program. [5]. In addition to this, a 360MW battery energy storage network system will be implemented which will assist in the government's plan to increase solar and wind power into the energy mix from its current 7.2% to 25.6% by 2030 [6].

Renewable energy sources especially photovoltaic generators are receiving attention and serve as suitable candidate for the replacement of coal fired generators for sustainable power generation. These generators have several advantages which include zero carbon emissions, noise free, have no signs of minimal degradation even after prolonged usage, and do not contain any moving parts thus requiring very little maintenance. However, these systems have limitations especially when used as a stand-alone system due to the inherent intermittent nature of PV generators. This undesirable feature results in varying output power and excessive frequency deviations which affect the normal operation of the power plant. This problem may be averted by hybridizing PV generators with alternative energy sources such as fuel cells, wind generators and battery storage systems [7] [8] [9].

Payne and Sheehan (1979) proposed a hybrid solar-wind system to achieve a more stable power system and decrease the back-up battery size. However, the economic benefit of such a system was not realized when compared with a stand-alone PV system. There are also concerns over the utilization of two systems which are both weather dependent. The pair also proposed a hybrid solar-diesel system, but they experienced compatibility issues [10]. Diesel generators have been discussed in literature as a possible candidate for back-up power for large PV arrays [11] [12], however the burning of diesel also raises environmental concerns. Fuel cells are a possible candidate to use in conjunction with PV generators and can address the problem of intermittent power from PV generators. Fuel cells have fast response capabilities and can produce electricity over an unlimited period to offer support to the PV supply due to its modular construction and flexibility. Thus, a constant continuous supply of power may be produced through a hybrid PV-fuel system despite weather conditions or the time of the day [13].

Different PV hybrid systems have been proposed in literature [13] [14] [15] and different topologies for the hybridization of different energy sources have also been studied [16] [17] [18] [19]. Two main topologies have been discussed extensively namely, AC Coupled and DC Coupled. In AC coupled systems, each of the power sources are connected to the AC grid by means of an AC-Busbar and each generator is an assigned a power converter responsible for conversion of DC to AC Voltage. In a DC coupled system the power sources and storage units are connected to a DC Bus-bar via DC-DC converters responsible for stepping up (boost) or stepping down (buck) the DC voltage to the desired output voltage. Similar to the AC coupled system, each of the power sources in this proposed topology are connected to individual power converters. Modular Hybrid power System Technologies have been considered [19] [20] [21] [22], this structure contains an energy bus and a communication bus. The energy bus connects each of the systems components with each other and the load demand. The communication bus connects all the system components and the load demand with a master controller. The master controller supervises all the signals, the system status and general control of the hybrid system. A common feature of the proposed systems is that each of the power sources make use of separate power electronic converters.

In recent years multi-port hybridized systems have been proposed [23] [24] [25] [26], these studies proposed parallel connections of different renewable energy power generators on a single DC Bus-bar. This research study aims to propose a MIMO DC-DC Converter for hybrid PV-Fuel Cell system topology and a control strategy to provide for a reliable, controllable, and sustainable power supply. This MIMO DC-DC Converter for hybrid systems is intended to overcome the problems of intermittent power which is inherent to PV systems and to propose an eco-friendly alternative to fossil fuel power generators.

1.2. PROBLEM STATEMENT

South Africa is currently facing a national problem where the energy utility is unable to meet consumer power demand, this has resulted in unplanned load reduction in the form of load shedding. This situation has propelled the government and many South Africans to explore alternative sources of power. Alternative renewable energy sources have been proposed especially Photovoltaic solar systems. Due to the intermittent nature of PV systems, single renewable energy systems have been rendered inefficient and less reliable. To overcome the intermittent power generation of PV systems, a diverse body of literatures have proposed integration of other energy sources resulting in hybrid systems such as PV-Wind Systems, PV-Diesel Systems and PV-Wind-Diesel systems. Fuel cells have received attention as a power source for hybridization with PV systems to improve overall system quality and sustainability. This research proposes a MIMO DC-DC Converter for hybrid systems and control strategies to provide for a reliable, controllable, and sustainable power supply. This MIMO DC-DC converter is intended to overcome the problems of intermittent power which is inherent to PV systems and to propose an eco-friendly alternative to fossil fuel power generators.

1.3. OBJECTIVES

1) To develop a Multi-input Multi-output DC-DC converter topology for hybridization of multiple energy sources.
2) To develop and compare two control strategies that will provide a reliable, controllable, and sustainable power supply.
3) To evaluate the efficiency of a 15kW MIMO converter system

1.4. HYPOTHESIS

1) Hybridization of multiple energy sources addresses and overcomes the issues of intermittency in renewable energy sources.
2) Hybridization of PV-Fuel cells with other energy sources such as fuel cells and wind power yield a stable system with zero interference between input ports of the power converter.
3) Hybrid energy systems provide a reliable, controllable, and sustainable power supply.

1.5. IMPORTANCE OF STUDY

The primary objective of this research endeavor is to undertake the design, modeling, and analysis of a Multi-input Multi-output (MIMO) DC-DC converter intended for application within hybrid photovoltaic (PV) and fuel cell energy systems. In conjunction with this, an intricate control strategy shall be formulated, and its effectiveness scrutinized to ensure the provision of a consistent, controllable, and sustainable power supply in grid-connected operational settings. This study assumes particular significance due to the imperative necessity to transition from conventional coal-fired power generation to more environmentally sustainable and renewable energy sources. Consequently, it is of paramount importance to comprehensively investigate the intricate interplay of renewable energy sources, such as the PV-Fuel Cell combination, prior to its practical implementation. The overarching aim of this research study is to proffer an innovative MIMO DC-DC Converter solution tailored to the specific requirements of hybrid energy systems, while concurrently presenting an optimized control strategy geared towards guaranteeing the consistent provision of dependable, manageable, and ecologically sustainable power.

1.6. DELIMITATIONS

- This study does not provide a comprehensive economic analysis and financial feasibility of hybrid systems. The object of the study is to investigate the interaction of multiple power sources in a system as a possible alternative to stand-alone PV systems and fossil fuel power plants.
- This study does not provide an analysis of different renewable sources.

1.7. RESEARCH METHODOLOGY

1.7.1. To develop a Multi-input Multi-output DC-DC Converter

To achieve this objective, the following strategies will be utilized:

- Generic Mathematical descriptions including those obtained from past studies will be employed for the mathematical models of each of the system components.
- Computer Software MATLAB/SIMULINK will be utilized to model and simulate the MIMO DC-DC converter:
- MATLAB/SIMULINK will be used to analyze the total system performance.

1.7.2. To develop and compare two control strategies for the MIMO DC-DC converter

To achieve this objective, the following strategies will be utilized:

- MATLAB/SIMULINK will be used to model a PID controller for the MIMO converter
- MATLAB/SIMULINK will be used to model a Fuzzy Logic Control for a dual input converter system.
- MATLAB/SIMULINK will be used to analyze the total system performance.

1.7.3. To evaluate the efficiency of the 15kW system

- MATLAB/SIMULINK will be used to obtain the measured values of the output voltage and output currents
- Manual calculations will be performed to calculate the efficiency of the 15kW system.

1.8. ADVANTAGES AND DISADVATAGES OF MIMO DC-DC CONVETERS

Table 1.1: Advantages and Disadvantages of MIMO DC-DC

	ADVANTAGES	DISADVANTAGES
1	Increased Efficiency: Multi-input multi-output (MIMO) DC-DC converters offer increased efficiency compared to single-input single-output (SISO) converters because they can combine power from multiple sources	Complex Design: MIMO DC-DC converters can be complex to design due to the multiple inputs and outputs, which may require complex control algorithms.
2	Improved Power Management: MIMO DC-DC converters allow for better management of power from different sources, enabling a more efficient use of available energy.	Increased Cost: Due to the complexity of the design and additional components required, MIMO DC-DC converters may be more expensive compared to SISO converters.
3	Increased Flexibility: MIMO DC-DC converters can be designed to work with a variety of input sources, such as solar	Higher Noise: Multiple inputs and outputs can increase the level of noise and

	panels, batteries, and fuel cells, which makes them a more flexible option for a range of applications.	electromagnetic interference, which can be a challenge to manage.
4	Higher Power Density: MIMO DC-DC converters can deliver high power density with less component count, which is a critical requirement in many applications.	Difficult to Control: Due to the multiple inputs and outputs, it can be challenging to control and regulate the output voltage and current to maintain stable operation.
5	Better Reliability: With multiple input sources, MIMO DC-DC converters can be designed with redundancy, making them more reliable in critical applications.	Limited Applicability: MIMO DC-DC converters may not be suitable for all applications, particularly those with a single power source, where SISO converters may be a more appropriate solution.

1.9. APPLICATIONS FOR MIMO CONVERTERS

A multiple input multiple output (MIMO) DC-DC converter can be used in various applications, some of which include:

A. Renewable energy systems: MIMO converters can be used in renewable energy systems such as wind and solar power systems to convert the DC voltage from multiple sources to the desired voltage level.

B. Electric vehicles: MIMO converters can be used in electric vehicles to convert the power from multiple batteries to the voltage and current levels required by the vehicle.

C. Telecommunications: MIMO converters can be used in telecommunications systems to efficiently convert and regulate the voltage levels required by various components of the system.

D. Industrial applications: MIMO converters can be used in industrial applications such as motor drives, robotics, and automation systems to efficiently regulate power and improve system performance.

E. Medical devices: MIMO converters can be used in medical devices such as implantable pacemakers and defibrillators to regulate power from multiple sources and improve device performance.

F. Aerospace and defence: MIMO converters can be used in aerospace and defence applications such as satellites, UAVs, and missiles to efficiently regulate power and improve system reliability.

G. Data centres MIMO converters can be used in data centres to convert and regulate the power supply to servers and other equipment, improving energy efficiency and reducing costs.

H. Consumer electronics: MIMO converters can be used in consumer electronics such as laptops, smartphones, and tablets to efficiently regulate power and improve battery life.

1.10. THESIS OUTLINE

CHAPTER 1: INTRODUCTION

- Background on the need for hybridization of renewable sources
- Importance of the study
- Research objectives, methodologies, and scope
- Advantages. Disadvantages and application of MIMO converters

CHAPTER 2: LITERATURE REVIEW

- Overview of renewable energy sources and MIMO Converters
- Previous studies on hybridization of renewable energy sources
- Identify gaps and limitations from previous studies

CHAPTER 3: MULTI-INPUT MULTI-OUTPUT DC-DC CONTROLLER DESIGN

- Derivation of proposed MIMO converter model
- Dynamic modelling of the PID controller

CHAPTER 4: MIMO CONVERTER WITH PID CONTROLLER SIMULATION AND DISCUSSION OF RESULTS

- MATLAB/SIMULINK model
- Comparative results of controller performance at different voltages

- Calculations of the system efficiency

CHAPTER 5: DUAL INPUT PV-FUEL CELL HYBRIDIZATION WITH FUZZY LOGIC CONTROL

- Fuzzy logic controller design
- MATLAB/SIMULINK model of hybrid PV-Fuel cell system with FLC
- Simulation results
- Comparative analysis of the transient response of the FLC and PID controllers

CHAPTER 6: CONCLUSION

- Summary of key findings and main contribution
- Recommendation for future studies

BIBLIOGRAPHY:

- List of cited work following the IEEE citation style

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

Due to the rising need for renewable energy, hybridized PV systems have been proposed [13] [14] [15] [16] [17] and have proven to have several advantages over single source renewable energy generators. Due to their capacity to solve the intermittent nature of standalone renewable energy sources, hybrid renewable energy systems have grown in favor. These systems integrate numerous renewable energy resources, including energy storage devices with solar, wind, hydro, or geothermal energy. Eliminating power supply fluctuations, boosting reliability, and optimizing system performance are the key goals of a hybrid system. Hybrid systems can offer a reliable and efficient power supply, cut costs, and support environmental sustainability by utilizing the complementing qualities of several energy sources and adding storage technology.

A hybridized renewable energy system that is dependable and sustainable can be created by merging two or more renewable energy sources such as photovoltaic (PV) cells and fuel cells. In this hybrid system, the fuel cells will activate automatically and supply the necessary power if the PV cells are unable to generate sufficient energy to meet the demands of the grid or the load. During periods of limited solar energy availability, such as at night or during adverse weather conditions, when the PV cells cannot meet the grid's requirements, fuel cells will seamlessly take over to ensure a consistent electricity supply [27].

Hybridization of PV and Fuel cells requires the use of power electronic converters. Several converter topologies have been proposed in literature, this includes hybridization using multiple DC-DC and DC-AC converters or more recently the interfacing of these renewable energy sources with multi-port power converters.

In this Chapter, a literature review of renewable energy sources such as PV-Systems, Fuel Cells and Power Electronic Converters is presented. Previous studies in multi-input multi-output converters will also be discussed.

2.2. PRINCIPLE OPERATION OF SOLAR-PV SYSTEMS

When photovoltaic cells are exposed to sunlight, photons are absorbed, which causes the ejection of electrons from their atoms. Then, as these electrons go through the cell, holes are formed. The photovoltaic effect, which is the flow of electrons within the cell that produces energy, is what gives solar cells their name. It demonstrates how solar energy is transformed into electrical energy. The electrons move in this process from the P-type material of the cell to the N-type material, where they continue on to a designated load by way of a circuit that is located externally [28].

Direct Current (DC) is generated from the Solar-PV cells and directly supplies DC loads. A DC-AC Inverter is used to convert the DC power in Alternating Current (AC). Moreover, a battery may be used as a storage device to store surplus electricity and may be used when additional power is required. The voltage and current flowing into the battery from the solar panels are controlled by a controller. as seen in Fig. 2-1.

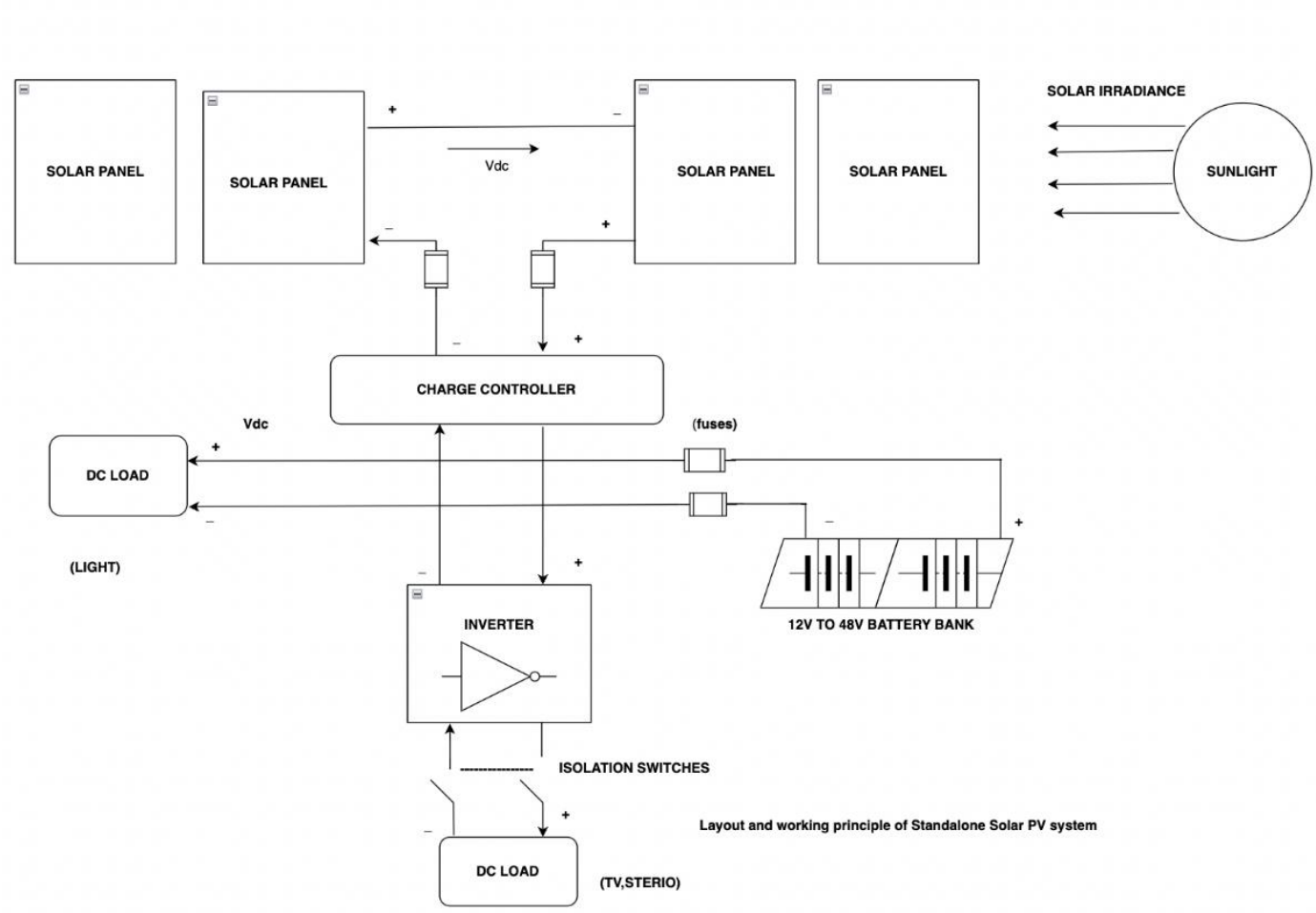

Figure 2-1: Layout and working principle of standalone Solar PV-Systems

2.2.1. Types of Photovoltaic Cells

Fig. 2-2. depicts the two main types of PV-Cells based on the technology used to manufacture them, namely: Thin Film Cells and Crystalline cells [29] . Crystalline cells are made of ultra-pure silicon. One PV-cell is made up of an average of 170 microns of silicon wafers. The abundance of silicon is an advantage of this type of PV-Cell. Thin Film Cells are made by adding up to 2 micrometers of semiconductor onto glass or stainless-steel plates. Thin Film cells are flexible and offer effortless installation and operation.

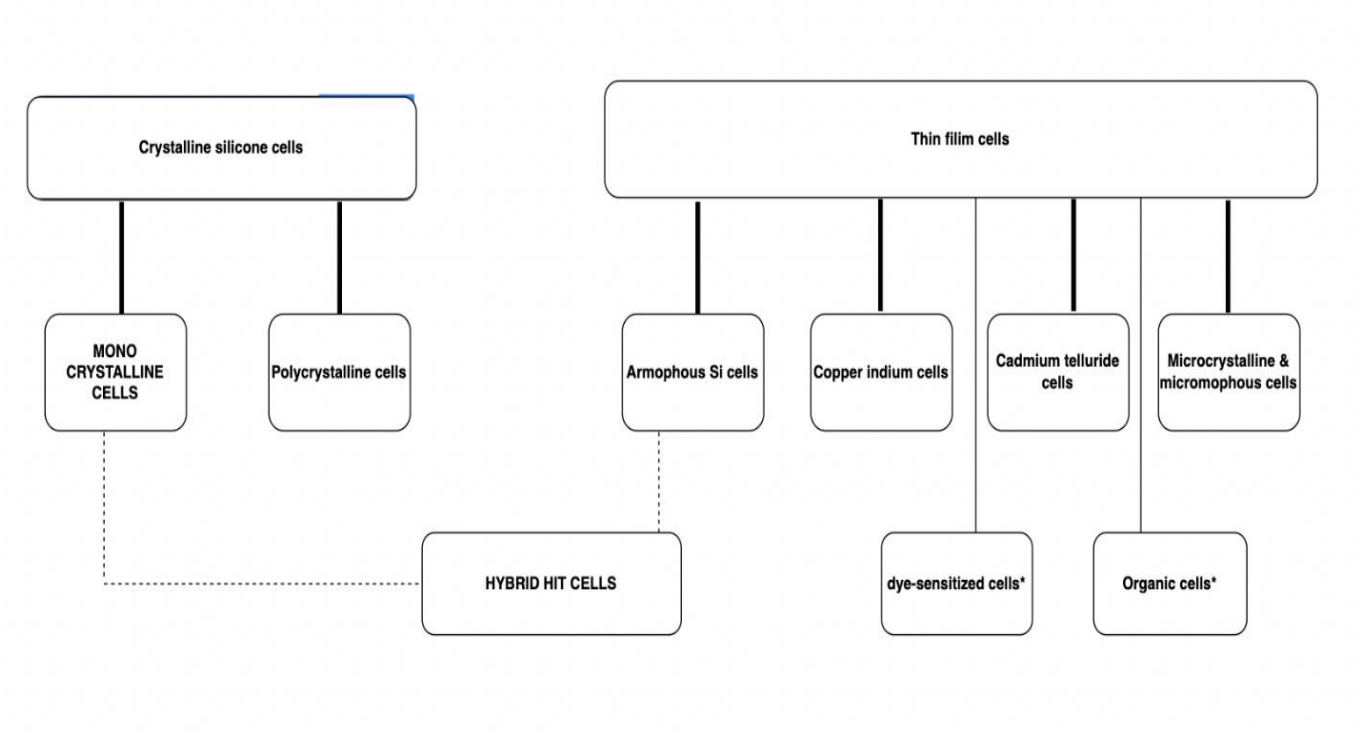

Figure 2-2: Two main types of PV cells

2.3. PRINCIPLE OPERATION OF A FUEL CELL STRUCTURE

Fuel Cells are similar to batteries because they produce DC power using an electrochemical conversion process. Hydrogen and oxygen in the atmosphere are drawn into the Fuel cell which in turn produces an electric current, water, and heat [30] . An electrolyte layer is present in a single-cell fuel-cell. The electrolyte is connected to the anode at the opposite end and the cathode on the other end. The anode is constantly fueled with hydrogen, while the cathode is supplied with oxygen from the atmosphere. As a result, when electrochemical reactions are initiated by electrodes a DC electrical current is generated as seen in Fig. 2-3.

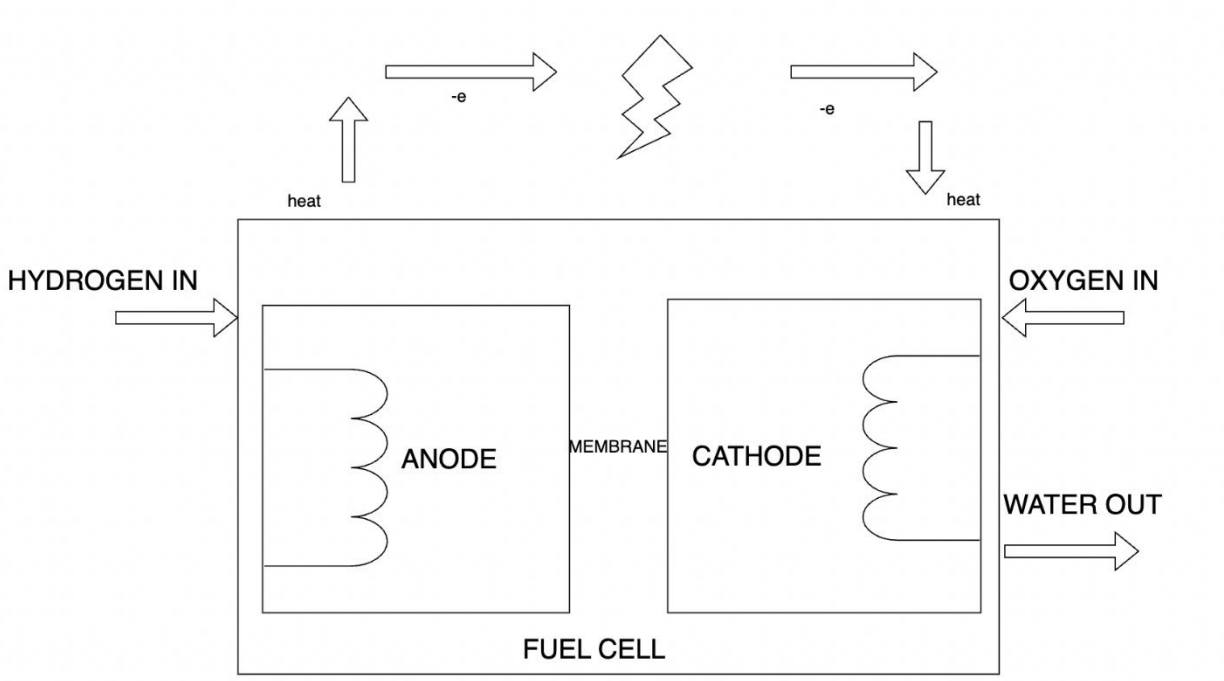

Figure 2-3: Basic Operation of a Fuel Cell

2.3.1. Types of Fuel-cells

There are five leading types of Fuel Cells, and they are distinguished by the type of electrolyte used in them [31] [32], which are:

1. Alkaline Fuel Cells (AFC)
2. Molten Carbonate Fuel Cells (MCFC)
3. Phosphoric Acid Fuel Cells (PAFC)
4. Proton Exchange Membrane Fuel Cells (PEMFC)
5. Solid Oxide Fuel Cells (SOFC)

The distinct features and application of the five identified types of Fuel-Cells are shown in the Table 1-1 below:

Table 2-1:Features and Application of Different Types of Fuel-Cells

	PEMFC	**SOFC**	**AFC**	**MCFC**	**PAFC**
Electrolyte	Polymer Membrane	Ceramic (Stabilized Zirconia)	Liquid Potassium Hydroxide (KOH)	Molten Carbonate	Liquid Phosphoric Acid
Catalyst	Platinum	Perovskites	Platinum	Nickel	Platinum
Operating Temperature ($°C$)	50-100	600-1000	90-100	600-700	150-200
Charge Carrier	H^+	O^{-2}	OH^-	$CO3^{-2}$	H^+
Cell Components	Carbon Based	Ceramic Based	Carbon Based	Stainless Steel	Carbon Based
Fuel	Methanol, H^2	H^2, CH^4, CO	H^2	H^2, CH^4	H^2
Electrical Efficiency (%)	25-35 (Stationary)	35-43	60	45	>40
Combined Power and Heat Efficiency (%)	70-90	<90	>80	>80	>85

Power Range (kW)	<1,000	10-100,000	1-100	100-100,000	50-1,000
Power Density ($mWcm2/$)	300-1,000	250-350	150-400	100-300	150-300
CO Tolerance	Poison	Fuel	Poison	Fuel	Poison
Balance of Plant	Low-Moderate	Moderate	Moderate	Complex	Moderate
Advantages	Solid electrolyte. Fast start-up. Low Temp.	Solid electrolyte. High efficiency. Flexible fuel & catalyst.	Higher performance due to alkaline electrolyte. Flexible catalyst.	High efficiency. Fuel & catalyst flexibility.	Tolerance to impurities of hydrogen.
Application	Backup & portable power. Vehicles. Small distribution.	Utilities. Auxiliary input. Large distribution.	Space. Military.	Utilities. Large distribution.	Distributed

2.4. DIFFERENT HYBRID POWER SYSTEMS ARRAYS

2.4.1. Photovoltaic-Battery-Diesel Hybrid System

Stand-alone PV systems are uneconomical due to their intermitted nature and dependence on specific weather conditions thus, a hybrid system is a better alternative. In case the solar system us unable to produce electricity, the diesel generator and battery may supplement the required power and make up for the power lost from the PV. If the demand exceeds the solar energy generator's design capacity and the solar energy system is sized for a particular load, the diesel generator may provide additional power. The diesel generator also serves as a charger to the batteries if the batteries are running low. It is important that the generator and batteries are designed and sized correctly to ensure system operational reliability [33].

Advantages of a Photovoltaic-battery-diesel Hybrid System:

- The operation of diesel generators is relatively not complicated and thus does not require industry experts to operate.
- Spare parts are abundantly available.
- Advance Battery technologies are commercially available.

Disadvantages of Photovoltaic-battery-diesel Hybrid systems

- Batteries have a shorter lifespan relative to other system components.
- Diesel generators have a poor yield percentage of needed power (+/-40%)
- Diesel generators are not environmentally sustainable due to the use of fossil fuel.
- Batteries emit harmful gases such as H_2 and O_2 and these are dangerous especially in confined spaces.

Figure 2-4 shows the arrangement of a Photovoltaic-battery-Diesel Hybrid System.

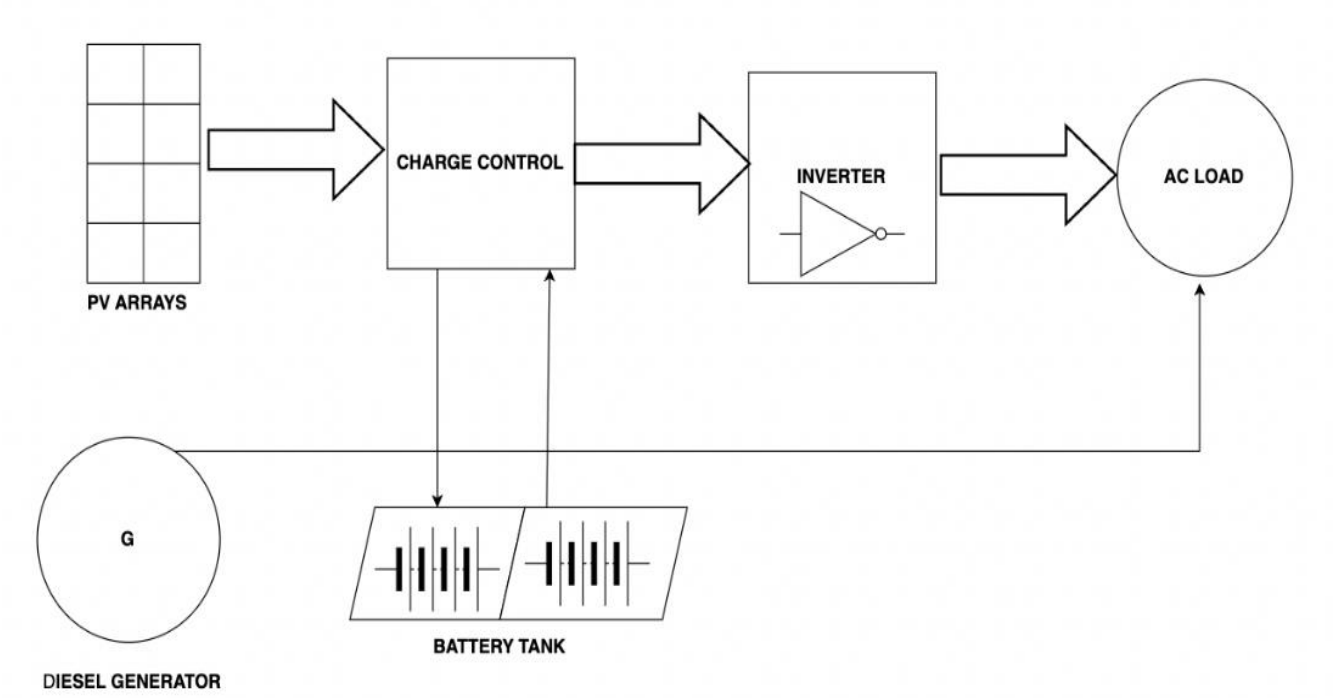

Figure 2.4:Photovoltaic-Battery-Diesel Hybrid System

2.4.2. Photovoltaic-Battery-Fuel Cell Hybrid System

As shown in Figure 2-5, a fuel cell serves as an additional source of power in this system, taking the place of a diesel generator. When the batteries are fully charged but the demand is greater than what the PV generator can handle, the fuel cell is turned on. Regarding PV size and battery availability, the benefits of this system are comparable to those of the Photovoltaic-Battery-Diesel. The key distinction between the two systems is that the diesel generator starts up more slowly and takes a few seconds to reach rated output. Fuel cells, on the other hand, take longer to start up and

need their output to rise steadily after starting. During operation, the temperature increases, and this improves the efficiency of the fuel cell considerably [34]

Fuel cells have high conversion efficiency compared to diesel generators. A 1kW diesel generator may reach between 8-15% efficiency, an equivalent Fuel Cell may reach up to 50% efficiency [10]. Diesel generators are not environmentally friendly due to high noise levels during operation and high emissions. Whereas fuel cells have very low noise levels and requires little maintenance.

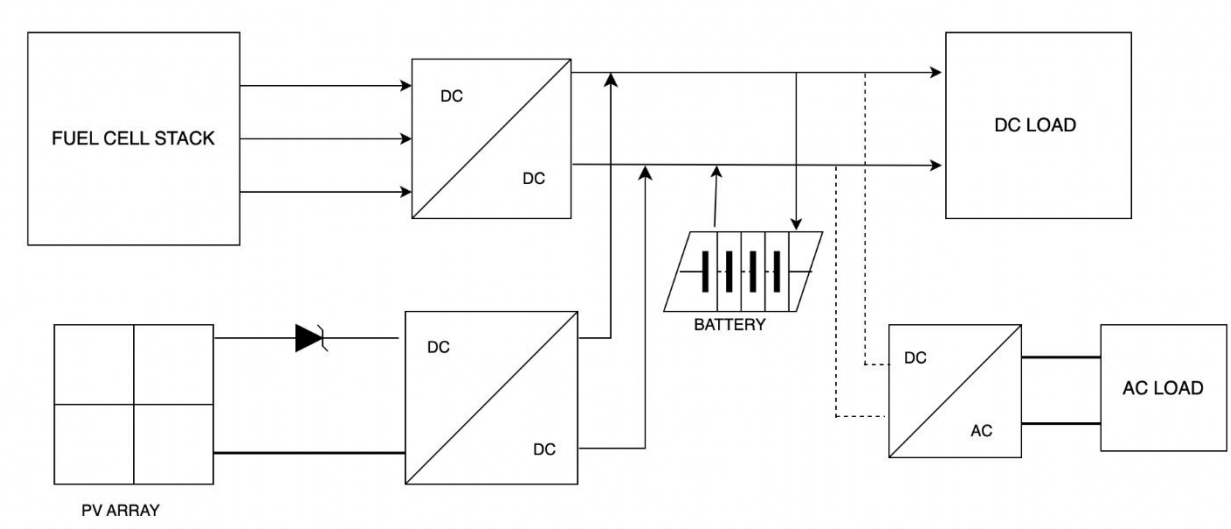

Figure 2-5: Photovoltaic-Battery-Fuel cell Hybrid System.

2.4.3. Photovoltaic-Electrolyzer-Fuel Cell System

An inadequate loss of feeding loads exists for certain uses. The system should be built to withstand adverse weather and demand conditions to achieve no deficiency of feeding load probability with a PV generator. As a result, energy storage requires a second energy source. In this method, excess

energy is converted through the electrolyzer and stored as compressed hydrogen. (See figure 2-6). Fuel cells are utilized when the demand exceeds the PV supply. Fuel cells may also serve as an emergency power source when that the PV generator fails.

With an efficiency of roughly 50%, this storage system can achieve the needed volume of storage while substantially decreasing the PV's capacity. [11]. The storage volume can thus be optimized based on the load requirements and weather conditions. It is possible to store both hydrogen and oxygen with this system, however due to costs, oxygen from the air is used to operate the fuel cells [9].

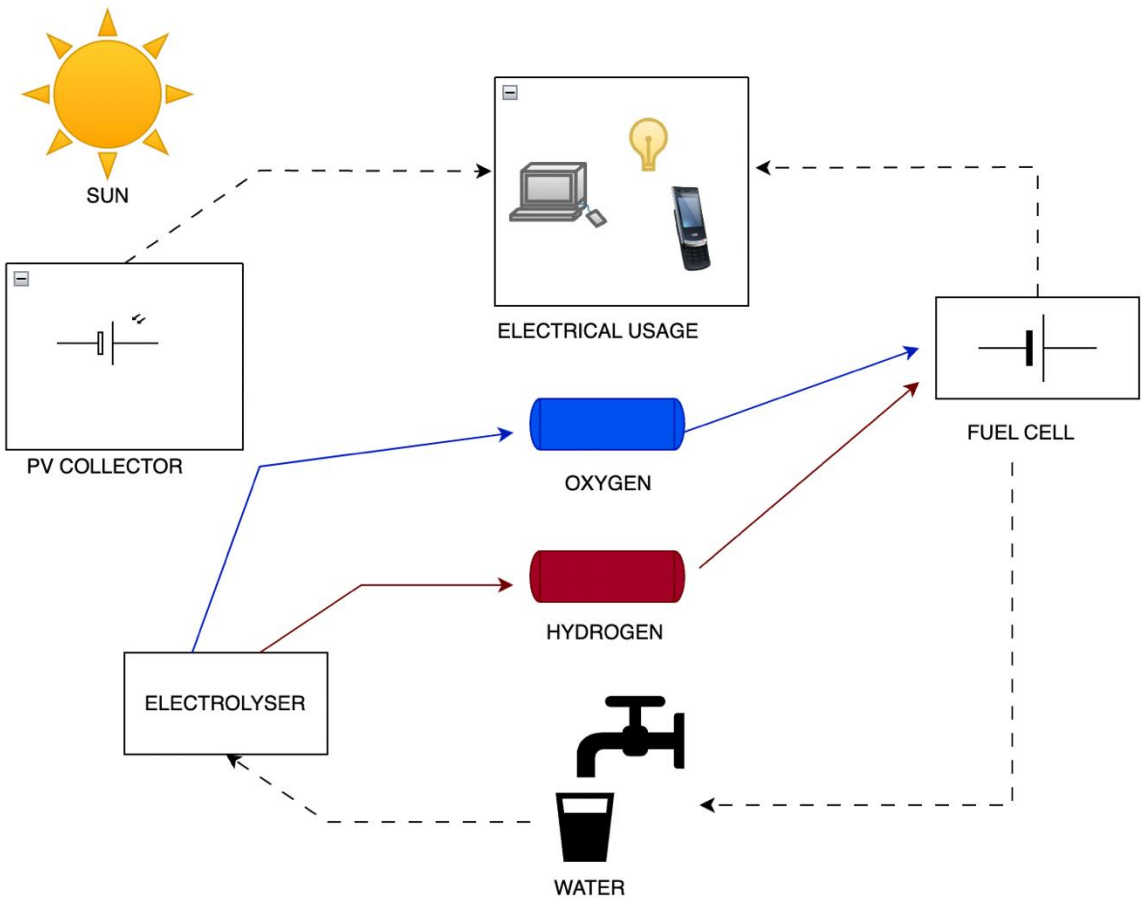

Figure 2-6: Photovoltaic-electrolyzer-Fuel Cell System

2.5. HYBRID POWER SYSTEM TOPOLOGIES

There two main types of topologies that are used to classify hybrid power systems which make renewable power sources namely DC or AC coupled topologies [12]. In DC topologies systems, power sources are connected to a DC busbar and from there are connected to the AC grid. In AC topologies, the power sources are connected directly to the AC grid.

2.5.1. DC Coupled System Topology

In this topology (see Figure 2-7), all the power sources are connected to the DC-Bus. If there are any AC power sources, the power is converted into DC using inverters and connected to the main DC bus together with all other power sources available. The output power from the DC-Bus is then converted into AC by means of DC-AC inverters to meet the required load voltage and frequency. The inverter should be sized to meet peak load demands. Each power source has its own DC-DC converter which is connected to the DC bus. It is worth noting that the DC-DC converter connected to the battery storage, or the Fuel Cell uses a bidirectional DC-DC converter, this configuration allows the battery to charge and discharge including fuel cells. These converters ensure that a constant DC voltage is supplied regardless of the varying voltage input from each of the power generators.

This topology's key benefit is that load demand is met continuously, even when the generators are charging the storage units. The main disadvantage of this topology is it low conversion efficiency. Furthermore, it is not desirable to add more power sources onto the system in an attempt to increase systems capacity because the nominal capacity of DC-AC inverters is limited [13].

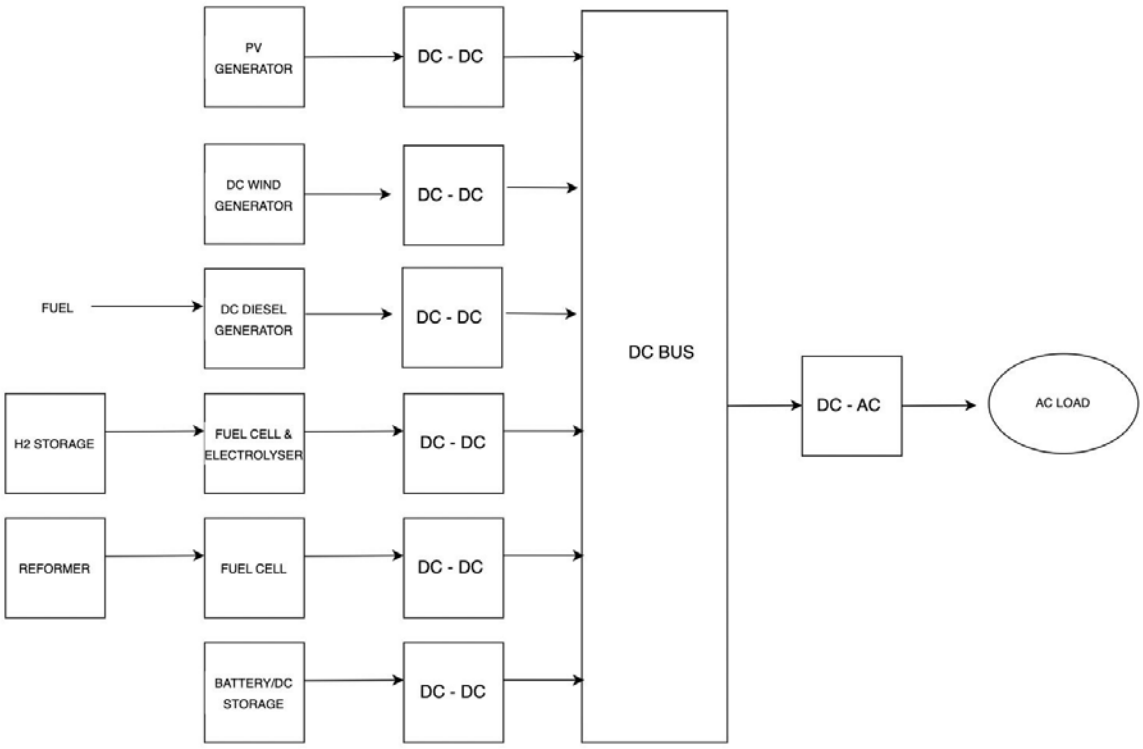

Figure 2-7: DC Coupled System Topology

2.5.2. AC Coupled System Topology

In figure 2-8 a AC-Bus-bar is used to connect generators to the AC grid.. This topology is superior to the DC because in this system the inverters for each of the power sources can be synchronized to its own generator to enable independent and simultaneous load supply with other inverters [18]. If the demand is low, the inverters switch to stand-by mode and only one or the necessary number of inverters required to meet the low load is active, for example all the inverters may be on standby while only the PV inverter is active to meet the low demand. Furthermore, during peak hours and high demand, all the inverters are active and run concurrently to meet the high demand. Due to this concurrent operation, the power conditioning unit and generator capacity are significantly reduced.

The advantages of this topology include high total efficiency, small PCU sizes while energy availability level is high and optimal diesel operation due to reduced operating time. Advanced PCU make it easier to control the system to ensure that load demand is met. Engler et al (1997) developed control algorithms which stabilize isolated grids and enable concurrent operation of multiple renewable energy sources and traditional generators [19].

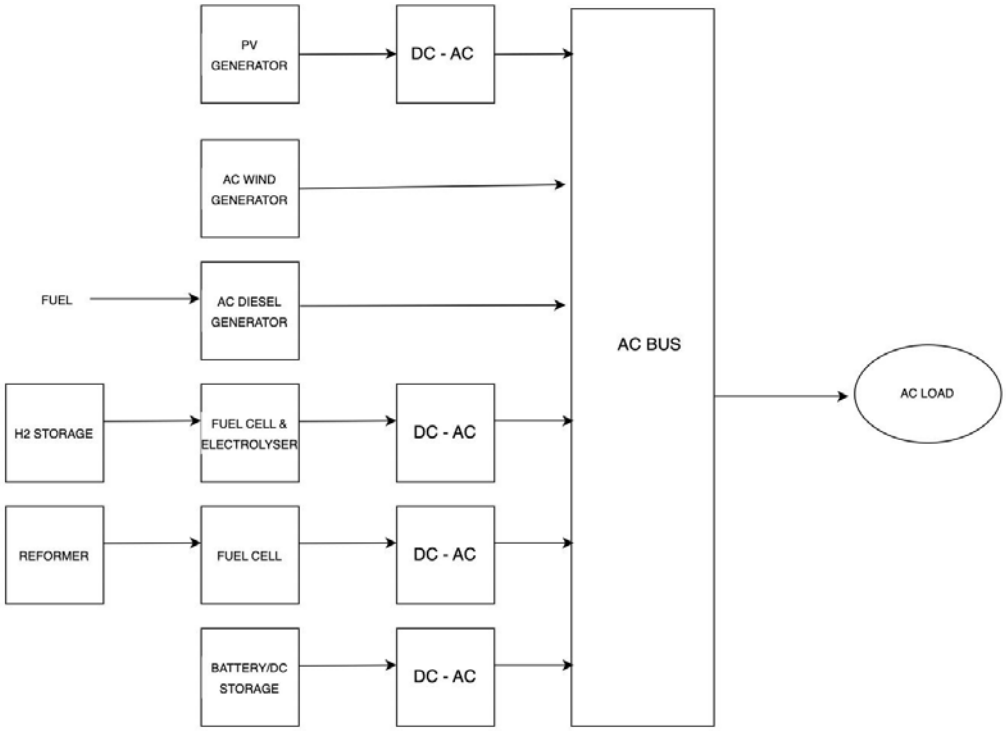

Figure 2-8: AC Coupled System Topology

2.6. MULTI-PORT STRUCTURES FOR PV-FUEL CELL HYBRIDIZATION

There are four common interface structures for hybrid PV-Fuel Cell systems for DC-AC conversion using power electronic converters (see Figure 10). The arrangement in Fig. 2-9(a) and (c) make use of single-port converters and (b) and (d) make use of dual-port converters. Chen et al. [35] [36] [37] [38] proposed that multi-port DC-DC converters can be applied in the arrangement in Fig. 2-9(b). With respect to Fig. 2-9(d), [39] [40] [41] proposed topologies which are befitting for single-phase AC loads and [42] [43] [44] proposed topologies best suited for three-phase loads. In the topology proposed by [42] the six switches in the inverter are not common sources and this in turn makes the drive more intricate. Five more switches where added by [43] and [45] [46] introduced 12 additional switches; this produced a three-phased AC output. Due to the high reliability [43], this system is able to supply the load even if when either of the input sources is disturbed. The proposed systems by [45] [46] are suitable for applications which require high power where no extra latent parts are utilized.

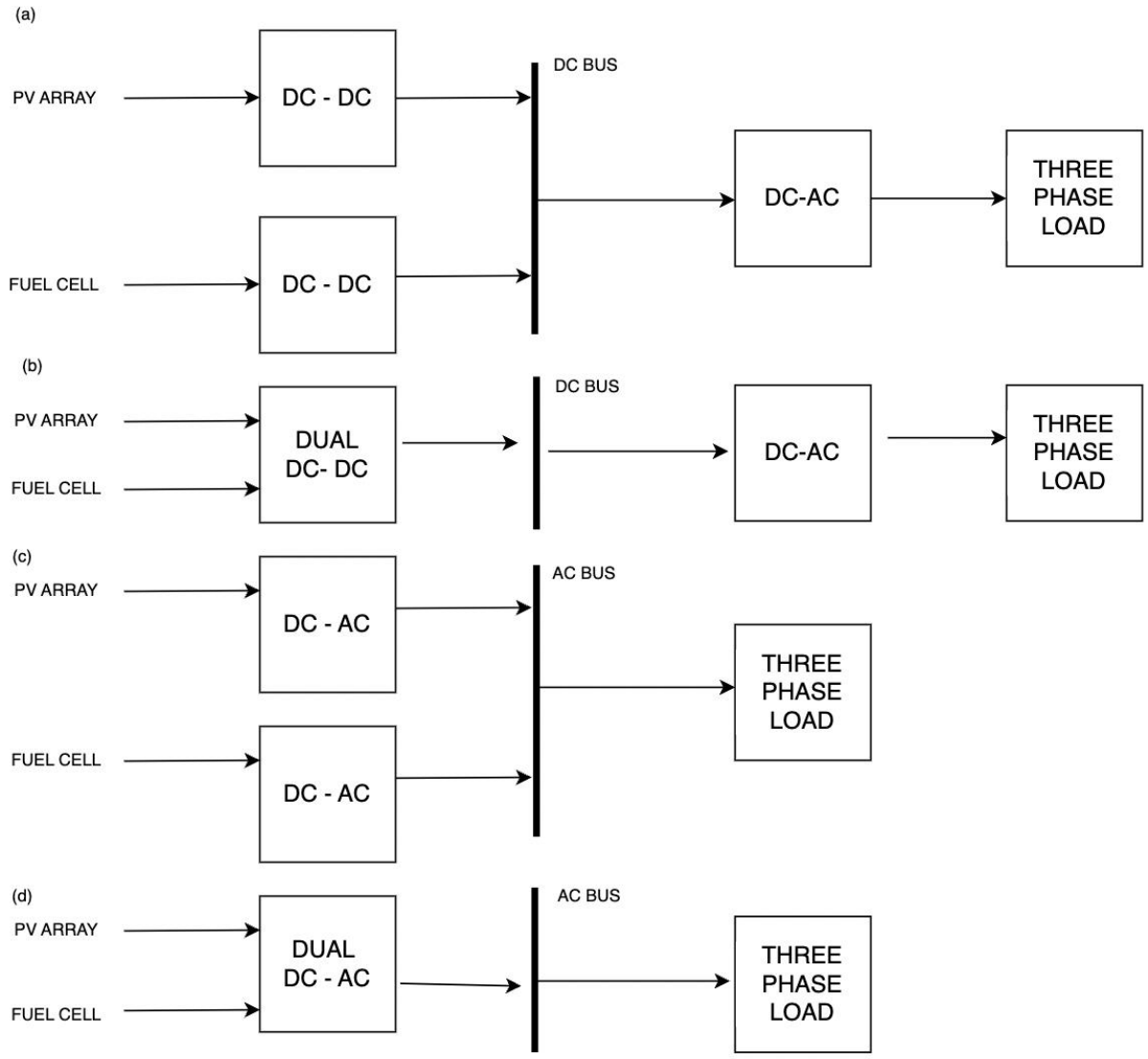

Figure 2-9: Different techniques for connecting hybrid PV-fuel cell systems to ac loads: (a) single-port DC-DC converters, (b) dual-port DC-DC converters, (c) single-port DC-AC converters, and (d) dual-port DC-AC converters [47].

2.7. OVERVIEW OF PREVIOUS STUDIES ON MIMO CONVERTERS

The demand for high-performance power electronic systems has increased in a number of applications, including smart grids, renewable energy systems, and electric vehicles. As a result, DC-DC converters with diverse input and output sources have been created. As opposed to conventional single-input single-output (SISO) converters, these converters, also known as multi-input multi-output (MIMO) DC-DC converters, offer greater flexibility, improved efficiency, and superior power management capabilities. Current research on MIMO DC-DC converters will be examined in this literature review, with an emphasis on various topologies, control strategies, and applications.

In the literature, several MIMO DC-DC converter topologies have been suggested. The multi-input buck-boost converter is one often used topology that combines the buck and boost converter designs to produce both step-up and step-down voltage conversion. For instance, a multi-input buck-boost converter was suggested in a study by [48] for a hybrid energy storage system, where several energy sources, such as batteries and supercapacitors, were merged to give enhanced power density and energy storage capacity. With distinct control loops for each input source, the proposed converter used a cascaded design of buck and boost converters to control the output voltage.

The multi-input forward converter topology, which makes use of the forward converter arrangement with numerous input sources, is another frequently used topology. A multi-input forward converter was suggested for renewable energy systems in a study by [49], where several renewable energy sources, such solar panels and wind turbines, were merged to offer a steady and dependable power supply. To provide effective power sharing among the input sources and to

control the output voltage, the proposed converter made use of a bidirectional switch and an input current sharing control method.

To ensure effective and dependable operation, MIMO DC-DC converter control approaches are essential. The literature has suggested several control methods, such as voltage-mode control, current-mode control, and hybrid control.

In MIMO DC-DC converters, voltage-mode control is a typical technique where the output voltage is used as the feedback signal to control the converter. For instance, a fuzzy logic controller was used to modify the duty cycles of the buck and boost converters based on the error between the target and actual output voltages in a work by [50], which presented a voltage-mode control method for a multi-input buck-boost converter. Under a variety of input and load circumstances, the proposed control technique increased dynamic performance while achieving quick response times.

Another common method used in MIMO DC-DC converters is current-mode control, in which the input or output currents are employed as the feedback signals to control the converter. For instance, a current-mode control technique for a multi-input forward converter was suggested in a work by [51], where the input currents of the various sources were monitored and used to control the output voltage. Accurate current distribution among the input sources was made possible by the suggested control method, which also guaranteed the converter's dependable operation under varying input and load conditions.

To profit from the advantages of both strategies, hybrid control techniques that integrate voltage-mode and current-mode control have also been suggested for MIMO DC-DC converters. For instance, in a work by [52], a hybrid control technique was suggested for a multi-input buck-boost

converter. Accurate output voltage regulation and effective input power sharing were achieved using a mix of voltage-mode and current-mode control. In comparison to individual control strategies, the suggested hybrid control approach outperformed them in terms of output voltage regulation, input power sharing, and dynamic response.

Due to their capacity to effectively manage many energy sources, Multi-Input Multi-Output (MIMO) DC-DC converters are becoming more and more popular in a variety of applications, including hybrid energy storage systems, electric vehicles, renewable energy systems, and microgrids. MIMO DC-DC converters offer flexibility, dependability, and high energy conversion efficiency by handling two or more input sources and numerous output loads. The study will explore the diverse MIMO DC-DC converter topologies, focusing on the developments and research findings within this field.

A common MIMO DC-DC converter topology is the Dual Active Bridge (DAB) converter, which consists of two high-frequency transformers and four power switches. It enables bi-directional power flow and provides galvanic separation between the input and output sides. To enhance the DAB converter's performance, numerous experiments have been done. To balance the voltage pressures on the switches, for instance, [48] developed a modified DAB converter with a centre-tapped transformer, leading to increased efficiency and decreased voltage stress on the switches. To maximize efficiency under various load conditions, [48] presented a DAB converter with a modified phase-shift control method. Additionally, cutting-edge control methods including model predictive control, fuzzy logic control, and sliding mode control have been used to improve the effectiveness, dynamic response, and fault tolerance of DAB converters. [53] [54] [55].

Another IMO DC-DC converter topology that may step-up or step-down multiple input voltages to a desired output voltage is the Multi-Input Buck-Boost converter. It has several input sources, numerous inductors, and a single output capacitor. To achieve high efficiency and dependable operation, researchers have proposed a variety of control algorithms for multi-input Buck-Boost converters. In a hybrid energy storage system, for instance, [12] suggested a voltage-mode control technique based on fuzzy logic to manage the output voltage and balance the input power among various sources. For multi-input Buck-Boost converters used in renewable energy systems, Wang et al. developed a current-mode control method that improved transient responsiveness and load regulation [13]. Additionally, hybrid control schemes integrating several control approaches, including as Maximum Power Point Tracking (MPPT), droop control, and pulse width modulation (PWM), have been suggested to maximize the performance of multi-input Buck-Boost converters [56] [57].

Another MIMO DC-DC converter topology that is appropriate for renewable energy systems is the multi-input forward converter. It has several transformers, numerous input sources, and one output inductor. To improve the performance of multi-input Forward converters, numerous experiments have been carried out. For instance, to achieve high efficiency and quick dynamic response in a multi-input Forward converter, [52] presented a hybrid control technique combining PWM and MPPT control. For a multi-input Forward converter in a renewable energy system, [56] proposed a fuzzy logic-based energy management technique that guaranteed optimal power sharing among various input sources and consistent output voltage regulation. Additionally, innovative control techniques including predictive control, sliding mode control, and resonant control have been used to enhance the efficiency, stability, and response time of multi-input Forward converters [53] [54] [55].

In the literature, other MIMO DC-DC converter topologies have also been suggested. As an illustration, the "input-series and input-parallel connections" topology suggested by [56] combines the input-series and input-parallel connections in a dual-input isolated forward converter, enabling effective power transfer from various input sources. For renewable energy systems [57] presented a dual-input resonant converter with soft switching that achieves high efficiency and lowers switching losses. A multi-input isolated full-bridge converter with an integrated transformer was presented by [58] to offer galvanic isolation between various input sources and the output load. For applications involving renewable energy, [59] suggested multi-input isolated DC-DC converters with magnetic integration, which provide increased power density and a smaller component count.

These are only a few illustrations of the different MIMO DC-DC converter topologies that have been researched in the literature. Each topology has unique benefits and drawbacks, and the best topology relies on the application's particular needs. The performance, effectiveness, and dependability of MIMO DC-DC converters for diverse renewable energy and other multi-input power systems are still being improved by additional research and development being conducted in this field.

2.8. PREVIOUSE STUDIES: FINDINGS AND GAPS/LIMITATIONS

2.8.1. Interleaved Converters: Principles and Applications

The paper [60] discusses the principles and applications of interleaved converters, emphasizing their advantages in reducing ripple currents and improving efficiency. The study provides theoretical analyses and experimental results to validate the performance of interleaved converters.

Gaps/Limitations:

- Limited discussion on control strategies for interleaved converters.
- Lack of analysis on the impact of interleaving on system dynamics and stability.
- Focus on specific applications without considering broader applicability.

2.8.2. Multi-Port Converters: Design, Control, and Applications

This paper [61] presents the design, control, and applications of multi-port converters, highlighting their flexibility in integrating various energy sources and loads. The study includes theoretical analyses, simulation studies, and experimental validations to demonstrate the performance and versatility of multi-port converters.

Gaps/Limitations:

- Limited focus on integration with renewable energy sources.
- Lack of comprehensive analysis on multi-port converter topologies.
- Insufficient exploration of advanced control algorithms for multi-port converters.

2.8.3. Hybrid Converters: Integrating the Best of Both Worlds

The paper [62] discusses hybrid converters that combine features of different converter topologies to achieve enhanced performance and flexibility. The study presents theoretical analyses, simulation results, and experimental validations to demonstrate the benefits and challenges of hybrid converters.

Gaps/Limitations:

- Limited exploration of optimization techniques for hybrid converters.

- Lack of comparative analysis with conventional converters.
- Insufficient consideration of thermal management and reliability issues.

2.8.4. Model Predictive Control in Power Electronic Converters

The paper [63] focuses on the application of Model Predictive Control (MPC) in power electronic converters, highlighting its potential to improve dynamic performance and efficiency. The study includes theoretical developments, simulation studies, and experimental validations to demonstrate the effectiveness and challenges of MPC in power electronic converters.

Gaps/Limitations:

- Limited discussion on real-time implementation challenges.
- Lack of consideration for hardware-in-the-loop simulation and testing.
- Insufficient exploration of robustness and adaptability of MPC algorithms.

2.8.5. Miniaturization and Integration of Multi-Input, Multi-Output Converters for Compact Power Electronic Systems

This paper [64] focuses on the miniaturization and integration of multi-input, multi-output converters to achieve compact and efficient power electronic systems. The study presents design methodologies, simulation studies, and experimental validations to demonstrate the challenges and solutions in miniaturizing and integrating MIMO converters.

Gaps/Limitations:

- Limited focus on thermal management and reliability in compact designs.
- Lack of exploration of integration challenges with other power electronic components.

- Insufficient consideration of cost implications and scalability of miniaturized MIMO converters.

2.8.6. Control Strategies for Multi-Input, Multi-Output Converters

This paper [65] investigates various control strategies for multi-input, multi-output converters, aiming to improve efficiency, stability, and dynamic response. The study presents theoretical analyses, simulation studies, and experimental validations to compare different control strategies and their impact on converter performance.

Gaps/Limitations:

- Limited exploration of advanced control algorithms and their implementation challenges.
- Lack of consideration for real-world applications and system integration.
- Insufficient analysis on the scalability and adaptability of control strategies for different converter topologies.

2.8.7. Fault-Tolerant Control in Multi-Input, Multi-Output Converters

The paper [66] focuses on fault-tolerant control strategies for multi-input, multi-output converters, emphasizing their importance in improving system reliability and robustness. The study includes theoretical developments, simulation studies, and experimental validations to demonstrate the effectiveness and challenges of fault-tolerant control in MIMO converters.

Gaps/Limitations:

- Limited discussion on fault detection and isolation techniques.
- Lack of exploration of adaptive and learning-based fault-tolerant control strategies.

- Insufficient consideration of real-time implementation challenges and hardware-in-the-loop testing.

2.8.8. Advanced Modulation Techniques for Multi-Input, Multi-Output Converters

This paper [67] investigates advanced modulation techniques for multi-input, multi-output converters to improve efficiency and reduce harmonic distortions. The study presents theoretical analyses, simulation studies, and experimental validations to compare different modulation techniques and their impact on converter performance.

Gaps/Limitations:

- Limited exploration of hybrid modulation techniques combining multiple modulation strategies.
- Lack of consideration for dynamic performance and stability under various operating conditions.
- Insufficient analysis on the implementation challenges and scalability of advanced modulation techniques.

2.8.9. Energy Management in Multi-Input, Multi-Output Converters for Hybrid Energy Systems

The paper [68] focuses on energy management strategies in multi-input, multi-output converters for hybrid energy systems, aiming to optimize the utilization of renewable energy sources and energy storage systems. The study includes theoretical developments, simulation studies, and experimental validations to demonstrate the effectiveness and challenges of energy management strategies in MIMO converters.

Gaps/Limitations:

- Limited exploration of coordinated control strategies for energy management in hybrid systems.
- Lack of consideration for real-world applications and system integration.
- Insufficient analysis on the scalability and adaptability of energy management strategies for different converter topologies.

2.8.10. Reliability and Durability Analysis of Multi-Input, Multi-Output Converters

The paper [69] investigates the reliability and durability of multi-input, multi-output converters, emphasizing the importance of robust design, material selection, and thermal management. The study includes theoretical analyses, accelerated life testing, and field measurements to assess the reliability and durability of MIMO converters.

Gaps/Limitations:

- Limited exploration of advanced reliability modelling and prediction techniques.
- Lack of consideration for environmental factors and operating conditions affecting reliability.
- Insufficient analysis on the impact of manufacturing variability and aging on converter performance.

2.8.11. Scalability and Flexibility of Multi-Input, Multi-Output Converters

This paper [70] focuses on the scalability and flexibility of multi-input, multi-output converters, exploring design methodologies and control strategies to adapt to varying power levels and load

conditions. The study includes theoretical analyses, simulation studies, and experimental validations to demonstrate the scalability and flexibility of MIMO converters.

Gaps/Limitations:

- Limited exploration of design optimization techniques for scalable and flexible MIMO converters.
- Lack of consideration for dynamic performance and stability under varying operating conditions.
- Insufficient analysis on the implementation challenges and cost implications of scalable and flexible MIMO converters.

2.8.12. Efficiency Optimization in Multi-Input, Multi-Output Converters

The paper [71] investigates efficiency optimization techniques in multi-input, multi-output converters, focusing on design methodologies, control strategies, and component selection to improve overall efficiency. The study includes theoretical analyses, simulation studies, and experimental validations to demonstrate the effectiveness and challenges of efficiency optimization in MIMO converters.

Gaps/Limitations:

- Limited exploration of advanced efficiency optimization techniques and their implementation challenges.
- Lack of consideration for dynamic performance and stability under varying load conditions.

- Insufficient analysis on the impact of component degradation and aging on converter efficiency.

2.8.13. Integration of Energy Storage Systems with Multi-Input, Multi-Output Converters

This paper [72] focuses on the integration of energy storage systems with multi-input, multi-output converters, aiming to optimize the utilization of renewable energy sources, improve system stability, and enhance grid support capabilities. The study includes theoretical developments, simulation studies, and experimental validations to demonstrate the effectiveness and challenges of integrating energy storage systems with MIMO converters.

Gaps/Limitations:

- Limited exploration of coordinated control strategies for energy storage integration in MIMO converters.
- Lack of consideration for real-world applications and system integration challenges.

Insufficient analysis on the scalability and adaptability of energy storage integration strategies for different converter topologies

2.8.14. Advanced Thermal Management in Multi-Input, Multi-Output Converters

The paper [73] investigates advanced thermal management techniques in multi-input, multi-output converters, focusing on thermal modelling, heat dissipation mechanisms, and thermal control strategies to improve reliability and longevity. The study includes theoretical analyses, thermal simulations, and experimental validations to assess the effectiveness and challenges of advanced thermal management in MIMO converters.

Gaps/Limitations:

- Limited exploration of advanced thermal modelling techniques and their integration with control algorithms.
- Lack of consideration for dynamic thermal behaviour under varying load conditions and operating environments.
- Insufficient analysis on the impact of thermal stress and aging on converter reliability and longevity.

2.8.15. Cybersecurity in Multi-Input, Multi-Output Converters

This paper [74] focuses on cybersecurity considerations in multi-input, multi-output converters, exploring potential vulnerabilities, attack vectors, and countermeasures to enhance system security and resilience against cyber threats. The study includes theoretical analyses, simulation studies, and experimental validations to assess the cybersecurity implications and challenges in MIMO converters.

Gaps/Limitations:

- Limited exploration of advanced cybersecurity techniques and their integration with control and communication protocols.
- Lack of consideration for real-world cybersecurity threats and attack scenarios specific to MIMO converters.
- Insufficient analysis on the impact of cybersecurity measures on system performance, reliability, and operational costs.

2.8.16. Hardware-in-the-Loop Simulation of Multi-Input, Multi-Output Converters

This paper focuses on hardware-in-the-loop (HIL) simulation techniques for multi-input, multi-output converters, exploring simulation methodologies, hardware integration, and validation procedures to assess and improve system performance and reliability. The study includes theoretical developments, HIL simulation studies, and experimental validations to demonstrate the effectiveness and challenges of HIL simulation in MIMO converters.

Gaps/Limitations:

- Limited exploration of advanced HIL simulation techniques and their scalability for complex MIMO converter systems.
- Lack of consideration for real-world applications and system integration challenges.
- Insufficient analysis on the impact of HIL simulation on system design, validation, and optimization processes.

2.9. CONCLUSION

In this chapter analysis of the several kinds of multi-input multi-output (MIMO) DC-DC converters and the range of control mechanisms used to maximize their performance was discussed. The importance of MIMO converters in meeting the rising needs for effective power conversion and management in contemporary electrical systems is highlighted by the in-depth research and developments in this area.

According to the studied literature, MIMO DC-DC converters have a number of benefits, such as higher power density, fewer components, and more flexibility when it comes to controlling numerous input and output sources. These advantages make them especially appropriate for uses

where effective power conversion and resource management are crucial, including in renewable energy systems, electric cars, and telecommunications.

Additionally, this review highlights the significance of intelligent and adaptive control methods in optimizing the performance of MIMO converters. The ability of several control strategies, including as sliding mode control, model predictive control, and digital signal processing methods, to regulate MIMO converters under various operating circumstances was also discussed. To guarantee steady functioning, quick transient reaction, and efficient power sharing between the input and output sources, these tactics are essential.

CHAPTER 3

MULTI-INPUT MULTI-OUTPUT DC-DC CONVERTER MODEL

3.1. INTRODUCTION

This chapter delves into the class of power electronic converters known as MIMO (Multi-input Multi-output) converters, which are renowned for their effectiveness and adaptability in a wide range of applications. To provide insights into the model and construction concepts of MIMO converters, the converter topology will be derived. The converters principle of operation will also be discussed. Mathematical models for the input and the output for the converter will be derived and the transfer functions for the output voltage controller will be presented.

3.2. DERIVATION OF PROPOSED MIMO BUCK CONVERTER

The proposed converter Figure 3-1 has two parts, *A* and *B* representing the multiple inputs and multiple output components of the circuit respectively. To derive the mathematical expressions of part *A* the converter, a Single Pole, Multiple throw (SPMT) switch will be used as seen in Figure 3-2. It should be noted only one of the three switches is active at any given instance [75]. The diagram makes use of two DC voltage sources for graphical demonstrative purposes of the proposed converter; renewable energy sources and energy storage systems can be used. It is worth noting that the proposed topology makes use of only one inductor on the input of the circuit, this is to ensure that the converter benefits from a high-power density. The analysis of this converter follows what has been proposed in literature [76].

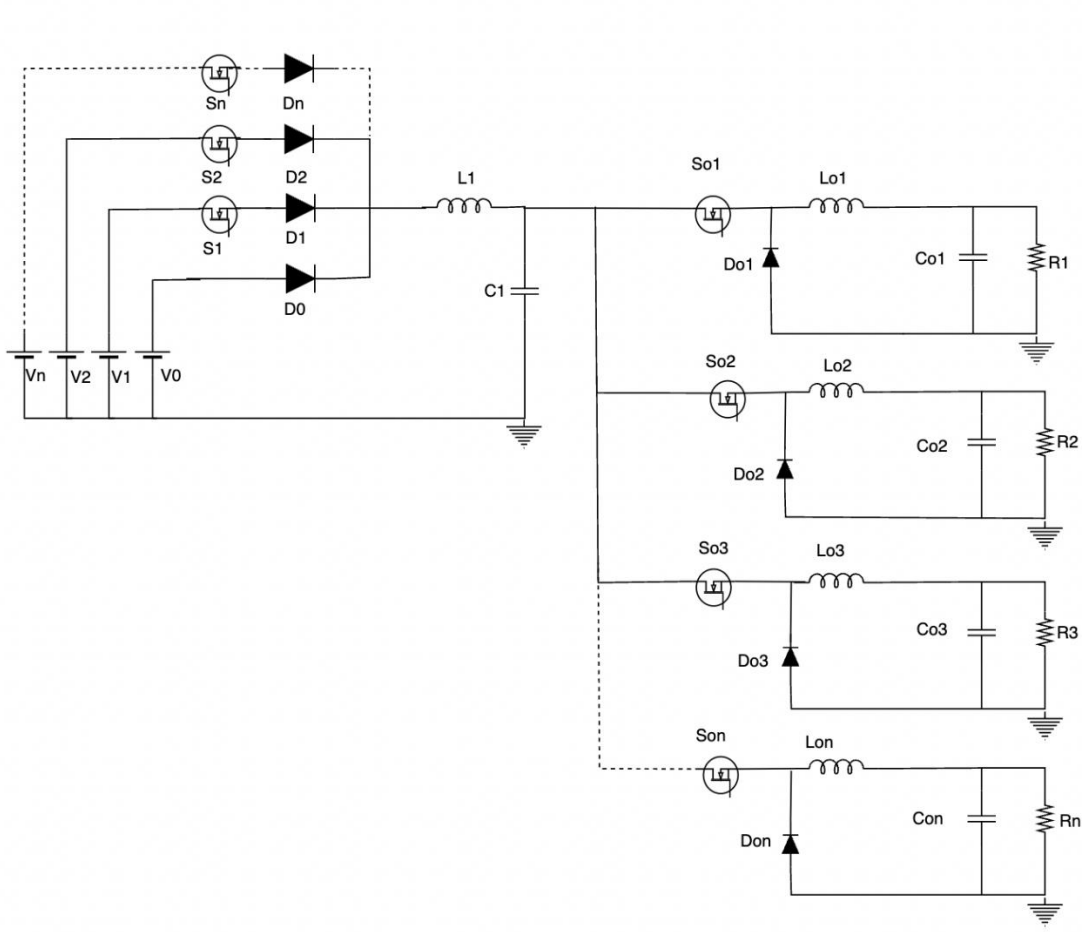

Figure 3-1: Proposed MIMO DC-DC Converter

Table 3-1 shows the different modes the input of the converter can be operated. Only one switch can be active an any given instance. When S_1 is active, only V_1 can deliver power to the circuit while the rest of the switches in the circuit remain inactive. If S_2 is active, only V_1 can deliver power to the circuit while rest of the switches remain inactive. This is true for all switch conditions up to the *nth* switch when the S_n is active V_n delivers power while the rest of the switches remain inactive. There is no voltage source linked to S_o therefore is used for the purpose of freewheeling and does not need to be included in the switching period, its parts can be included in Modes I to nth.

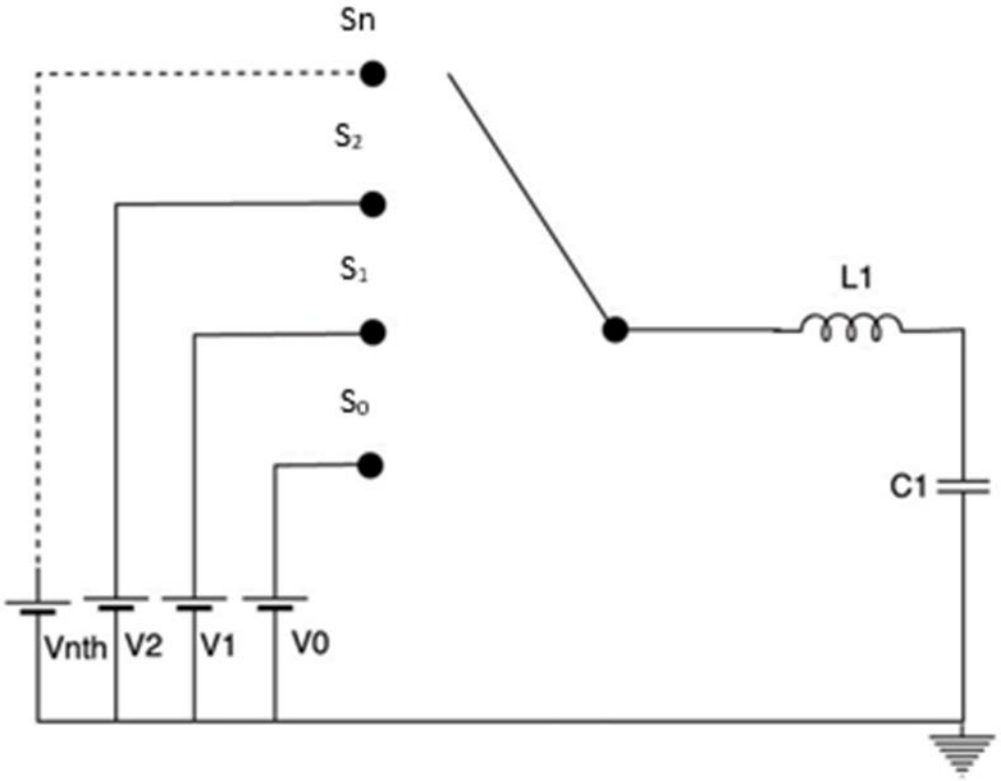

Figure 3-2: SPMT Switch

Table 3-1: Different modes for input operation

Mode	ON Switch	V_L	Active Voltage Source
0	S_0	$-V_o$	Freewheeling
I	S_1	V_1-V_o	V_1 delivers power
II	S_2	V_2-V_o	V_2 delivers power
nth	S_n	V_n-V_o	V_n delivers power

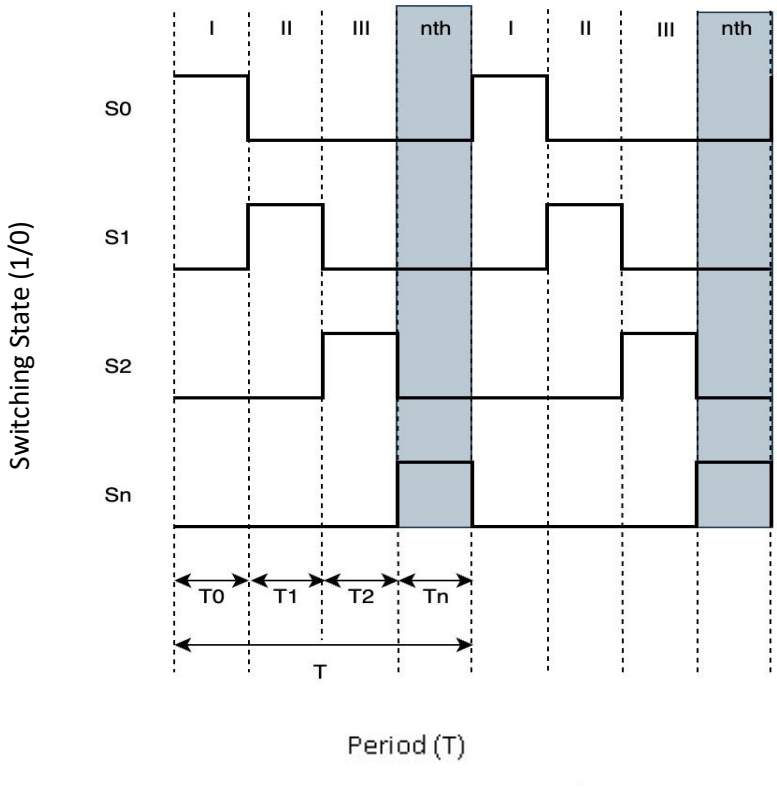

Figure 3-3: Switching patterns of proposed converter.

Figure 3-3 shows the possible switching patterns of the proposed MIMO buck converter. T_0 represents the ON time for S_0, T_1 represents the ON time of switch S_1, T_2 represents the ON time for S_2 and similarly T_n will represent the ON time for S_n.

Therefore,

$$T_0 = d_0 * T$$

$$T_1 = d_1 * T$$

$$T_2 = d_2 * T$$

$$T_n = d_n * T \quad (1)$$

$$T_{total} = T_0 + T_1 + T_2 + \cdots + T_n \quad (2)$$

T represents the switching period and d_0, d_1, d_2 and d_n are the corresponding duty cycles of S_0, S_1, S_2 and S_n respectively. The following equation can be derived from Figure 3-3, Table 3-1 and the volt-second balance equation since an inductor follows the volt-second balance principle [77] [78]:

$$T_0(-V_0) + T_1(V_1 - V_0) + T_2(V_2 - V_0) + \cdots + T_n(V_n - V_0) = 0 \quad (3)$$

Applying simplification gives the following equation:

$$V_1 * T_1 + V_2 * T_2 + \cdots + V_n * T_n = V_0(T_1 + T_2 + \cdots + T_n) \quad (4)$$

Finally, an equation that shows the relationship between the input and output voltages can be obtained by combining (1), (2) and (4):

$$V_0 = d_1 * V_1 + d_2 * V_2 + \cdots + d_n * V_n \quad (5)$$

V_o is the voltage across capacitor C, hence,

$$V_C = V_0 \quad (6)$$

This concludes part *A* of the circuit.

To obtain the mathematical expression of part *B* of the circuit, only one switch can be active, and the rest of the switches will remain inactive, i.e. If S_{o1} is ON, S_{o2}, S_{o3} up to S_{on} will be OFF and the analysis will be done on the circuit corresponding to the active switch. In Figure 3-4, it can be seen that S_{o1} has two operating states namely Mode I where S_{o1} is ON and Mode II where S_{o1} is OFF.

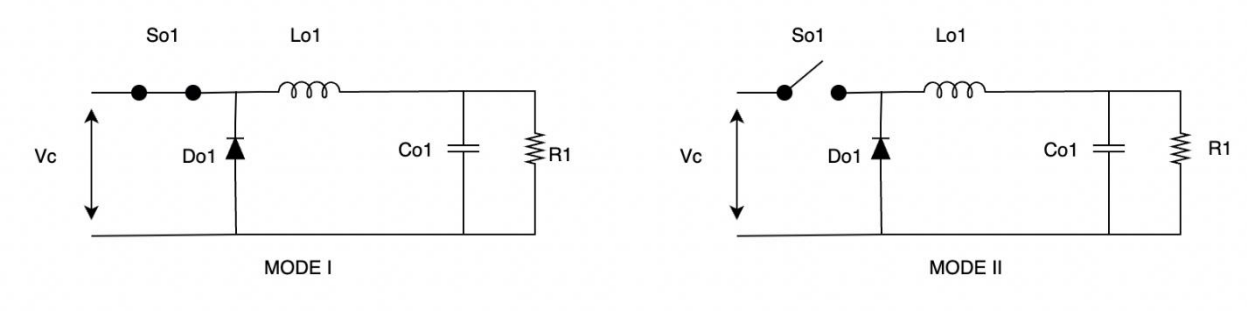

Figure 3-4: *Two switching modes for buck converter output*

When S_{o1} is ON, applying Kirchhoff's Voltage Law (KVL) results in the following equation:

$$-V_C + V_{L01} + V_{O1} = 0 \quad (7)$$

$$I_{C1} - I_{L01} + I_{O1} = 0 \quad (8)$$

Thus,

$$V_{L01} = V_C - V_{O1} \quad (9)$$

$$I_{C1} = I_{L01} + I_{O1} \quad (10)$$

\When S_{o1} is OFF, applying Kirchhoff's Voltage Law (KVL) results in the following equation:

$$V_{L01} = -V_{O1} \quad (11)$$

$$I_{C1} = I_{L01} + I_{O1} \quad (12)$$

Applying the Volt-second balance principle for the ON and OFF states, the following equation is formulated:

$$V_{L1(ON)} * T_{ON} + V_{L1(OFF)} * T_{OFF} = 0 \quad (13)$$

Where,

$$D = \frac{T_{ON}}{T} \tag{14}$$

$$T_{ON} = DT \tag{15}$$

Substituting equations (9), (11) and (15) into (13) results in:

$$(V_C - V_{O1})(DT) + (-V_{01})(1 - D)T = 0 \tag{16}$$

$$V_{O1} = DV_C \tag{17}$$

Substituting (5) and (6) into (17) gives us the final output voltage when S_{i1} is ON, and the rest of the switches are OFF:

$$V_{O1} = d_1 * V_1 + d_2 * V_2 + \cdots + d_n * V_n \tag{18}$$

This equation applies to all the output voltages when one switch is ON, and the rest are OFF up to the nth term. It follows then if S_{on} is ON, and the rest of the switches are OFF the final output is:

$$V_{On} = d_1 * V_1 + d_2 * V_2 + \cdots + d_n * V_n \tag{19}$$

3.3. PID CONTROLLER DESIGN AND DYNAMIC MODEL

Figure 3-5 shows the controller feedback loop that was chosen to control the output voltages of the converter. To obtain the controller transfer function $G_{\text{n,}}$ the dynamic states of the system output were modelled and linearized to obtain the transfer function G_{In} of the output states.

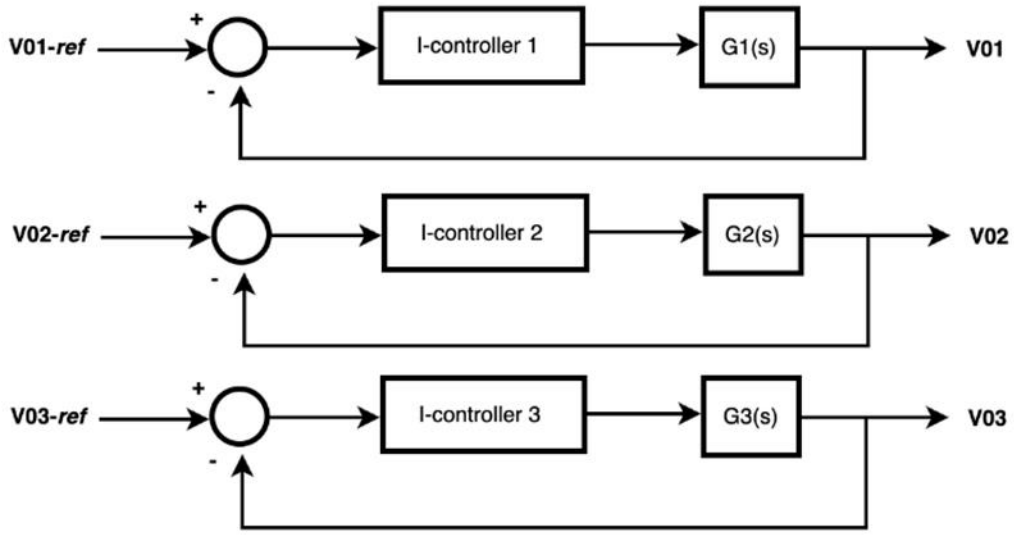

Figure 3-5: Integral Controller feedback closed loop.

From Figure 3-1 and Figure 3-4 the differential equations of the inductor current and capacitor voltage are derived as follows:

Inductor Current:

$$\frac{di_{Ln}}{dt} = \frac{1}{L_n}[(V_{In} - V_{cn}) + (-V_{cn})(1-d)] \tag{20}$$

$$\frac{di_{Ln}}{dt} = \frac{V_{In}}{L_n}d - \frac{V_{cn}}{L_n} \quad , \forall n \in \mathrm{Z} \tag{21}$$

Capacitor Voltage:

$$\frac{dV_{cn}}{dt} = \frac{1}{C}\left[\left(i_{ln} - \frac{V_c}{R_n}\right)d + \left(i_{ln} - \frac{V_{cn}}{R_n}\right)(1-d)\right] \tag{22}$$

$$\frac{dV_{cn}}{dt} = \frac{1}{C}(i_{ln}) - \frac{V_{cn}}{R_n L_n} \quad , \forall n \in Z \tag{23}$$

For linearization and simplifications, the state equations are rewritten in standard forms where;

$$i_{ln} = x_1 \tag{24}$$

$$V_{cn} = x_2 \tag{25}$$

$$d_u = u \tag{26}$$

$$y = V_c = x_2 \tag{27}$$

The state equations are written with the new variables from the standard forms

Inductor current:

$$\frac{dx_1}{dt} = -\frac{1}{L_n}x_2 + \frac{V_{in}}{L_n}u \tag{28}$$

Capacitor Voltage:

$$\frac{dx_1}{dt} = \frac{1}{C}(x_1) - \frac{1}{R_n L_n}x_2 \tag{29}$$

These equations are both linear as the satisfy the test for linearity which are homogeneity and superposition where,

$$f(0) = 0 \tag{30}$$

$$f(a+b) = f(a) + f(b) \tag{31}$$

The Laplace transform of the state equation was taken to find the transfer function G_{In} of the outputs.

Inductor current

$$sX_1 = -\frac{1}{L_n} + \frac{V_{in}}{L_n}u(s) \tag{32}$$

Capacitor voltage

$$sY(s) = \frac{1}{C_n}X_1 - \frac{1}{R_nC_n}Y(s) \tag{33}$$

By simplifying and substituting (33) into (32) the result is:

$$sC_nY(s)\left(s + \frac{1}{R_nC_n}\right) = -\frac{1}{L_nC_n}Y(s) + \frac{V_{in}}{L_n} \tag{34}$$

Therefore,

$$G_{In}(s) = \frac{Y(s)}{U(s)} = \frac{\frac{V_{in}}{L_nC_n}}{s^2 + \frac{1}{R_nC_n}s + \frac{1}{L_nC_n}} \tag{35}$$

The next step is to derive the integral controller transfer function G_n of the closed loop system.

Input: $Y_{ref}(s)$

Output: $Y(s)$

The basic equation for this closed loop system is,

$$Y(s) = G_{In}(s)G_n(s)\left(Y_{ref}(s) - Y(s)\right) \quad (36)$$

By substituting (35) into (36) and simplifying we get the following equation.

$$\frac{Y(s)}{Y_{ref}(s)} = \frac{G_{n(s)}\frac{V_{in}}{L_nC_n}}{s^2+\frac{1}{R_nC_n}s+\frac{1}{L_nC_n}+G_n\frac{V_{in}}{L_nC_n}} \quad (37)$$

The transfer function of an integral controller is given as

$$G_n(s) = \frac{K_i}{s} \quad (38)$$

Therefore, by substituting (38) into (37) we get the transfer function:

$$\frac{Y(s)}{Y_{ref}(s)} = \frac{\frac{V_{in}K_i}{L_nC_ns}}{s^2+\frac{1}{R_nC_n}s+\frac{1}{L_nC_n}+\frac{V_{in}K_i}{L_nC_ns}} \quad (39)$$

3.4. CONCLUSION

This chapter introduced and modeled a Multi-Input Multi-Output (MIMO) DC-DC converter, presenting its topology, operational modes, and switching patterns. Utilising a Single Pole, Multiple Throw (SPMT) switch, the converter manages multiple inputs and outputs efficiently. A PID controller feedback loop was proposed for voltage regulation, with its dynamic model and transfer function derived. Overall, this chapter provides a framework for the design and control of the proposed MIMO converter.

CHAPTER 4

MIMO SIMULATION AND DISCUSSION OF RESULTS

4.1. INTRODUCTION

This research proposed MIMO-Buck Converter that is adapted for inputting multiple renewable dc energy sources and energy storage systems. The simulation results were obtained from using three input dc sources, V_1 = 350V, V_2 = 400V, V_3 = 500V where V_1 is Solar-PV, V_2 is the Fuel Cell and V_3 is a battery. This converter works with other energy sources including Wind, diesel, and energy storage systems. The switching commands for the input switches S_1, S_2 and S_3 are obtained from fixed duty ratios of 0.3, 0.4, 0.5 respectively and the switching frequency is 100KHz. The values of the input inductor L=200µ H and input Capacitor C = 80µ F were calculated as discussed in [79] .

The controller is designed to output multiple DC voltage of different standard and non-standard battery voltages. In this simulation, standard battery voltages were used, and an Integral controller designed in such a manner to achieve three output voltages V_{01}, V_{02} and V_{03} to be 110V, 48V, 24V respectively. The values of the inductors L_{o1} = 1.11 mH L_{o2} = 2.046 mH and L_{o3} = 3.64 mH, the capacitors $C_{o1} = C_{o2} = C_{o3}$ = 200µF, and the load R_1 = 1.04 ohm, R_2 = 1.08 ohm and R_3 = 1 ohm were calculated as discussed in [79].

MATLAB/Simulink software was used to obtain the simulation results of the MIMO Buck Converter using three inputs and three outputs which includes the input voltage variations to examine the performance of this Integral controller controlled closed-loop system.

4.2. BLOCK DIAGRAM

Figure 4-0 shows the block diagram for the proposed converter

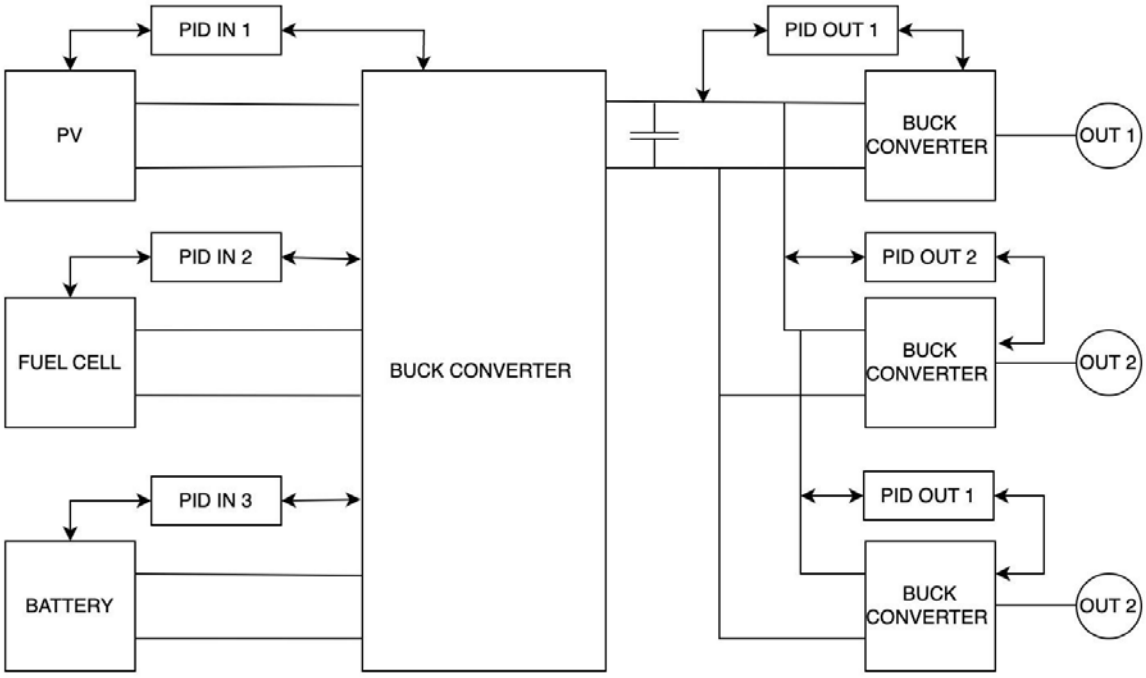

Figure 4-1: Block diagram of proposed converter

4.3. SIMULATION RESULTS

MATLAB/SIMULINK was used to simulate the model wherein three inputs and three outputs were used to demonstrate the operation of the MIMO converter.

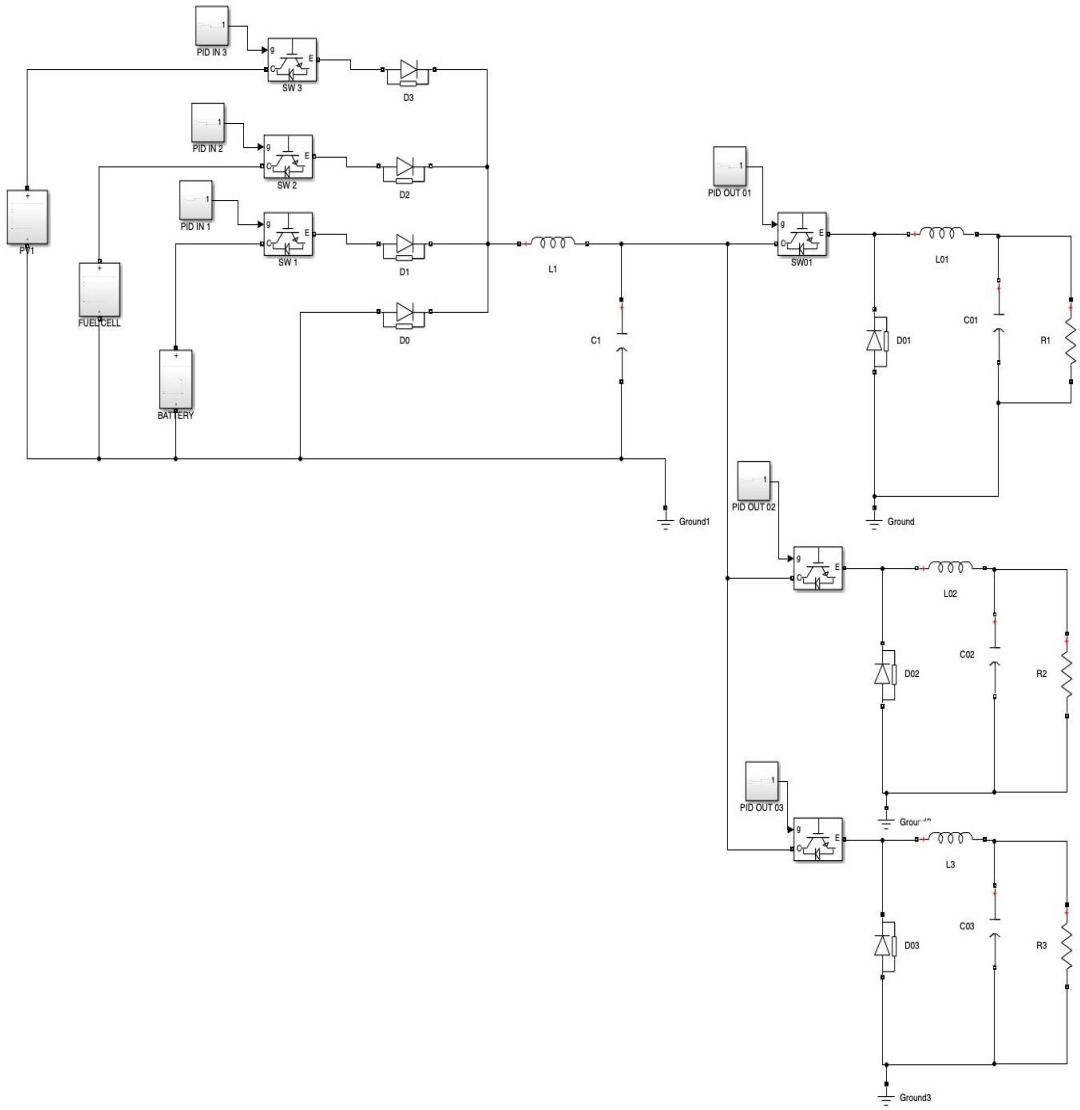

Figure 4-2: MATLAB/Simulink of proposed converter

4.2.1. Result 01

In this simulation study, the transient response of the MIMO converter under transient conditions, specifically considering the sequential activation of power sources, has been examined. The sequential activation, with V_1 initiated at 0.9s, followed by V_2 at 0.6s, and V_3 at 0.25s, presented a complex scenario to evaluate the converter's ability to adapt and maintain stability.

The dynamic response, as depicted in Figure 4-3, demonstrates the performance of the MIMO converter equipped with a PI controller. The sequential activation of V_1=500V, V_2=400V, and V_3=350V, illustrated in Figure 4-2, showcased the converter's capacity to uphold the desired output voltages (V_{01}=24V, V_{02}=28V, and V_{03}=110V) with a high degree of precision and resilience.

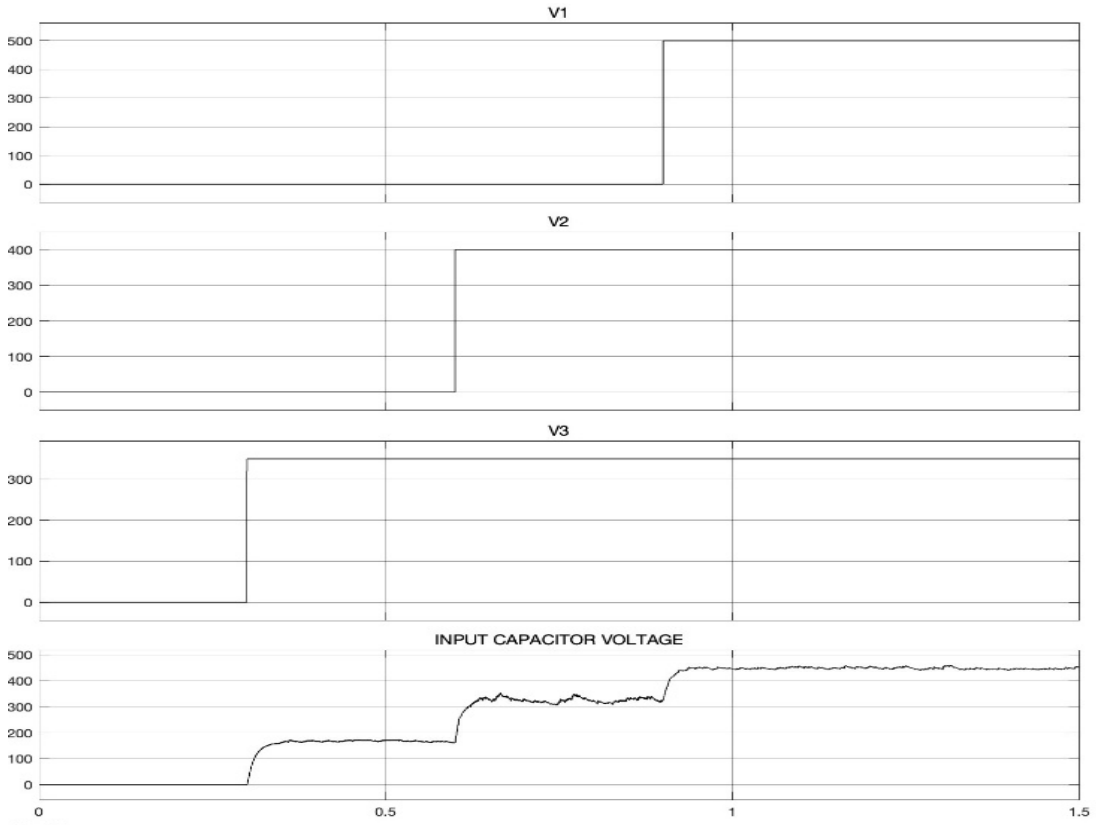

Figure 4-3: MIMO Converter input voltages and capacitor voltage

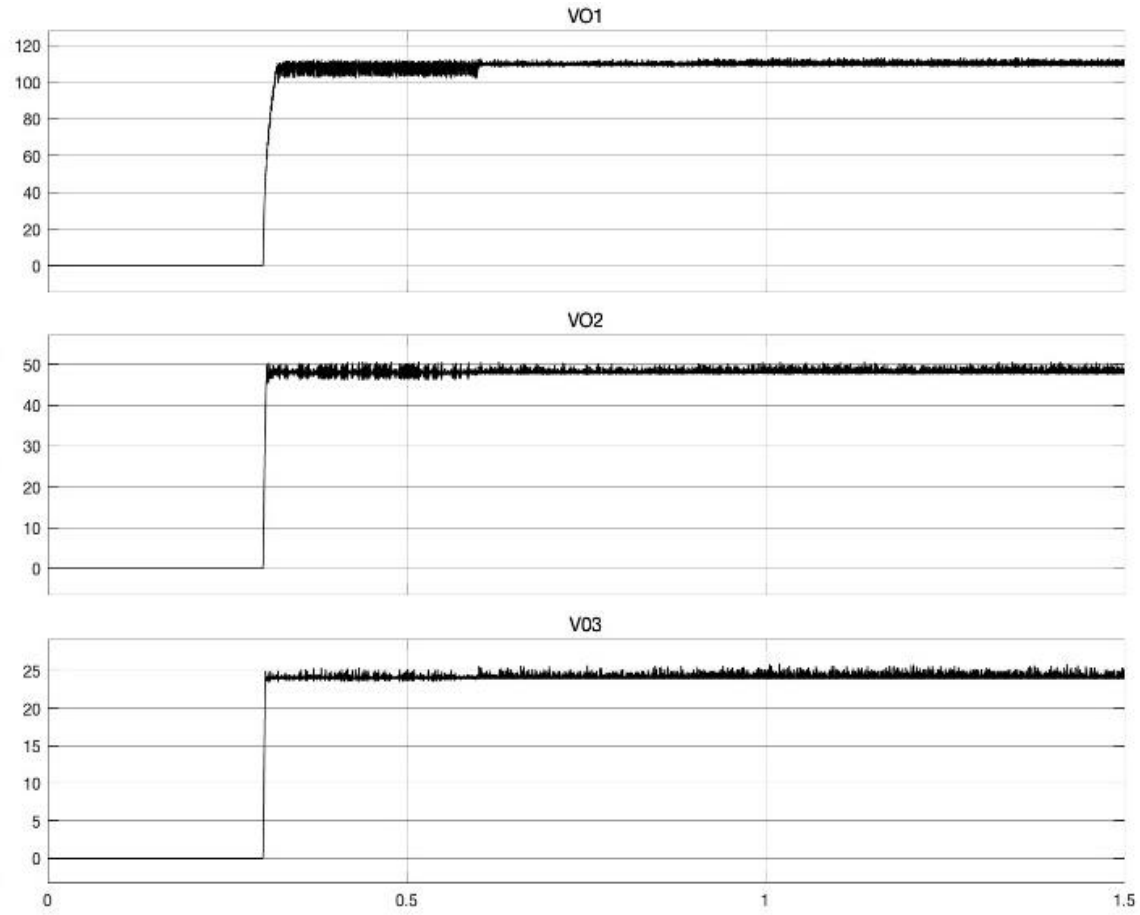

Figure 4-4: MIMO Converter output voltage waveforms

4.2.2 Result 02

In this simulation, an analysis was conducted with all three energy sources active from the initial stage. The deactivation sequence commenced with V_3 at 0.25s, followed by V_2 at 0.6s, and concluding with V_1 at 0.9s, all while maintaining an operational phase of V_1 at 1000rad and a temperature of 25°C. This deliberate deactivation sequence was designed to scrutinize the performance of the MIMO converter under transient conditions as each power source is

sequentially deactivated. The examination encompassed an evaluation of the converter's output voltage, input inductor voltage, and input voltages corresponding to each power source.

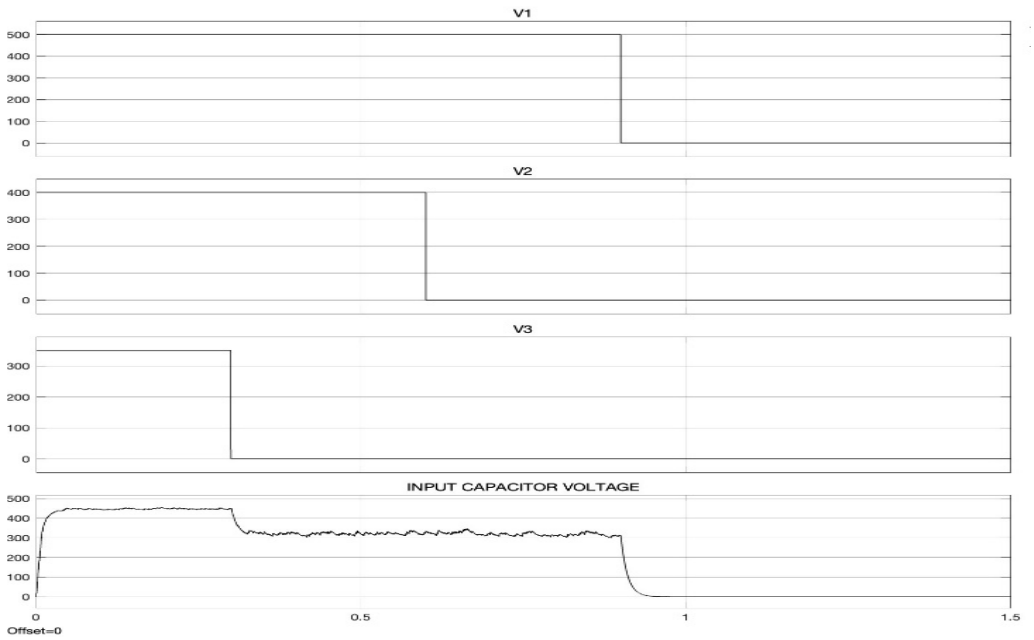

Figure 4-5: MIMO Converter input voltages and input capacitor waveforms

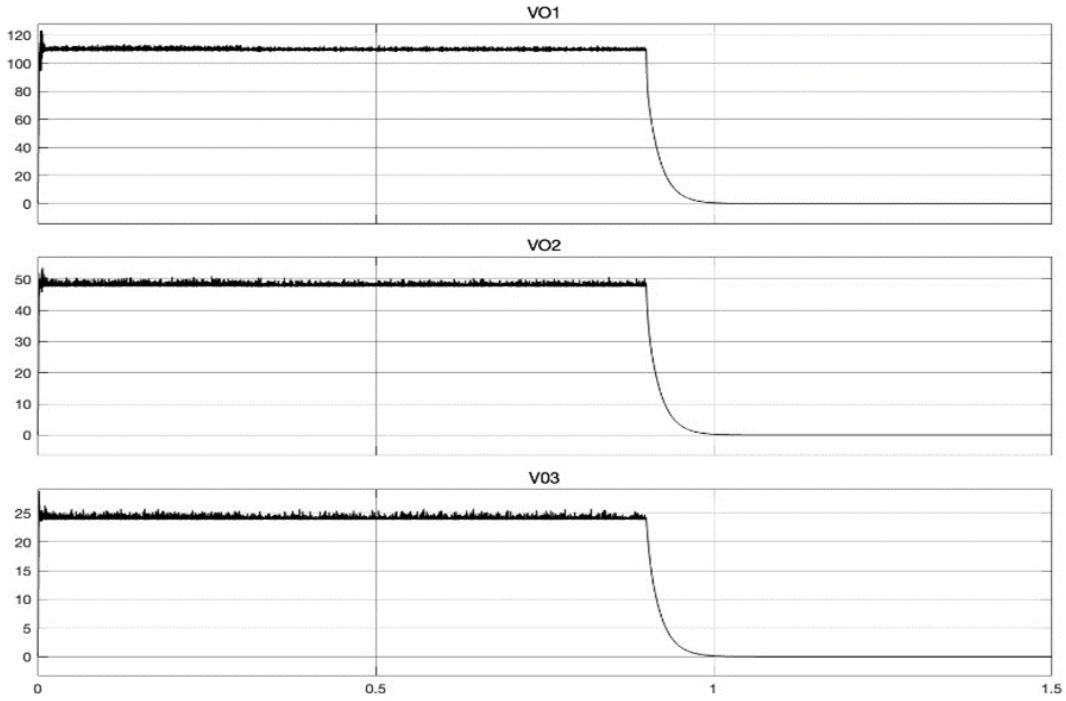

Figure 4-6: Output voltages of MIMO Converter

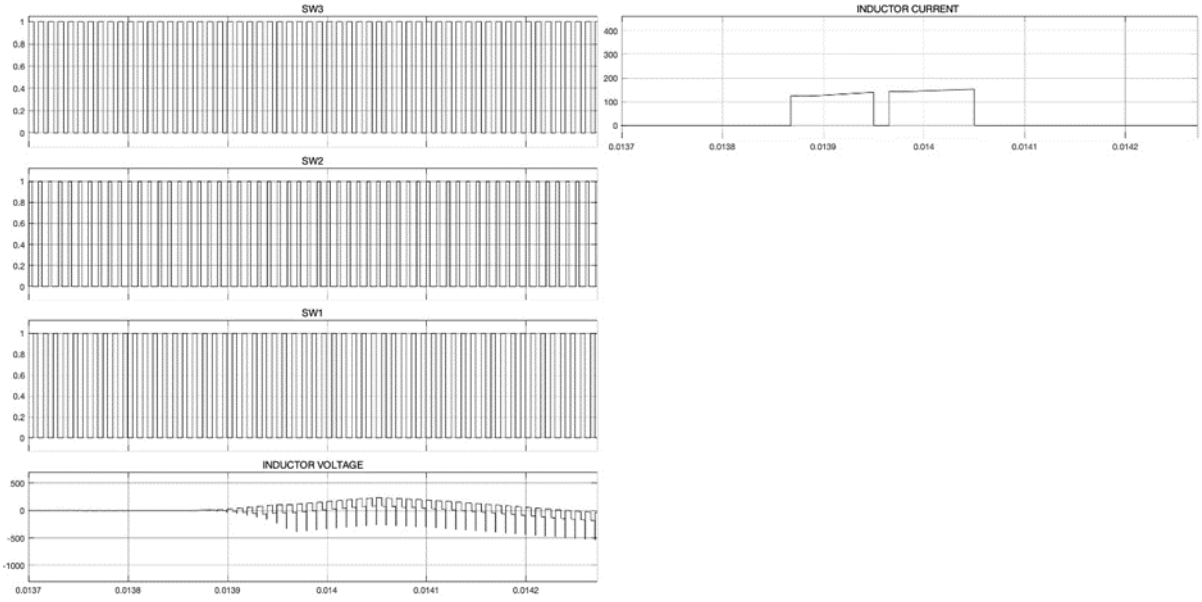

Figure 4-7: Input inductor voltages and currents

4.4. DISCUSSION OF RESULTS

The proposed control strategy for the MIMO DC-DC converter has undergone thorough evaluation across diverse transient conditions. In this investigation, the behavior of input switches SW_1, SW_2, and SW_3, controlled by a fixed pulse-generated switching scheme with distinct duty cycles, and output switches SW_4, SW_5, and SW_6, regulated by PI-controllers, was studied. The simulation, executed using MATLAB/SIMULINK, focused on two critical transient scenarios: the sequential activation of three input sources from a LOW state and the sequential deactivation of three input voltages from a HIGH state.

4.4.1. Result 01 discussion

The converter demonstrates an ability to effectively mitigate disturbances arising from the sequential activation of power sources, revealing a robust design that minimizes deviations in the dynamic response.

The observed minimal overshoot and oscillations in the dynamic response underscore the converter's stability and efficiency in transient scenarios. This signifies not only the successful integration of a PI controller but also the effectiveness of the proposed converter design in ensuring a smooth and controlled response during variations in power source activation. As power systems often encounter dynamic conditions, these findings affirm the converter's suitability for real-world applications, providing engineers and researchers with valuable insights for the design and optimization of MIMO converters in dynamic energy systems.

4.4.2. Result 02 discussion

The dynamic response of the MIMO converter, as illustrated in Figure 4-3 with a PI controller, is a focal point of the results. Figure 4-6 shows the switching patterns of SW1, SW2 and SW3 and the input inductor voltage and current. The sequential deactivation of V1=500V, V2=400V, and V3=350V, as depicted in Figure 4-2, provides insights into the converter's ability to sustain the desired output voltages (V01=24V, V02=28V, and V03=110V) the despite disturbances induced by the consecutive deactivation of power sources. Notably, the analysis reveals a dynamic response characterized by minimal overshoot and oscillations, indicating the robustness of the proposed converter in handling transient scenarios.

In conclusion, the deliberate deactivation sequence of power sources and subsequent analysis has provided insights into the dynamic behavior of the MIMO converter. These findings contribute to an understanding of the converter's stability, responsiveness, and capacity to maintain desired output voltages under transient conditions. Such knowledge is instrumental for engineers and researchers involved in the design and optimization of MIMO converters for real-world applications where transient conditions are inherent in power systems.

The MIMO DC-DC converter, equipped with PI-controllers, consistently demonstrated its capability to maintain constant output voltages in accordance with predefined battery voltage setpoints (V_{01}=24V, V_{02}=48V, and V_{03}=110V) under all tested conditions. The dynamic response showcased minimal overshoot and observable oscillations, highlighting the exceptional performance of the designed controller. A high efficiency of 95.63% is particularly beneficial for this system, signifying that a significant portion of the input power is efficiently converted to the desired output, minimizing energy losses, and enhancing overall system performance.

The designed controller can be modified to create a monolithic multi-input, multi-output DC-DC buck converter by adding more sources and loads. This demonstrates the flexibility of the MIMO DC-DC converter and the potential for it to be used in various applications.

4.5. SYSTEM EFFICIENCY

The system effeciency was calculated for 3 inputs and 3 outputs over one cycle for a 15kW system. The measured and calculated values are as follows:

$V_1 = 500V \;\; I_1 = 20.97A \;\; P_1 = 10485W$

$V_2 = 400V \;\; I_2 = 4.9A \;\; P_1 = 1960W$

$V_3 = 350V \;\; I_3 = 7.3A \;\; P_3 = 2555W$

$V_{01} = 110V \;\; I_{01} = \;\; 105.77A \;\; P_{01} = 11634.62W$

$V_{02} = 48V \;\; I_{02} = 44.44A \;\; P_{02} = 2133.33W$

$V_{03} \;\; = 24V \;\; I_{03} = 24A \;\; P_{03} = 576W$

$efficiency = \frac{14343.95}{15000} \; x \; 100 = 95.63\%$

An efficiency of 95.63% was achieved in the modelling of the 15kW MIMO converter. This high efficiency indicates that the converter effectively minimizes energy losses during conversion, resulting in more economical and sustainable operation.

4.5. CONCLUSION

MATLAB/Simulink model and simulations results of the proposed converter were investigated and presented. The Simulation results included the case where each of the input sources are active at consecutive time intervals and where the input sources were deactivated consecutively. The results further demonstrate how the converter would perform when each of the power sources operate independently and when paired with other sources. Results of the zoomed output and input switching states, input inductor voltage and current were also shown for each the combinations followed by the output and input voltages and the zoomed-out waveforms of the output switches, output inductor voltage and current were shown. Furthermore, the system efficiency was calculated based on absolute values of voltages and current demonstrating that the converter has a high efficiency.

CHAPTER 5

DUAL INPUT PV-FUEL CELL HYBRIDIZATION

5.1. INTRODUCTION

The MIMO Converter proposed in Chapter 4 is analyzed under a hybrid PV-Fuel cell system. The chapter delves into this process of designing a Fuzzy Logic Controller (FLC) for a multi-input multi-output (MIMO) DC-DC converter. It outlines the three fundamental steps involved in FLC design which are fuzzification, FLC interference and Defuzzification. Additionally, the MATLAB Simulink model of the converter is introduced, providing a practical framework for our controller design and evaluation. As the core objective of this chapter, we will compare the performance of the Fuzzy Logic Controller to that of an Integral Controller in the context of the proposed MIMO DC-DC converter. This comparative analysis aims to assess the benefits of FLC in achieving precise and adaptive control when dealing with multiple input sources. By evaluating the two control strategies, we can highlight the strengths and weaknesses of each and determine which is better suited for the specific demands of our multi-input multi-output system.

5.2. FUZZY LOGIC CONTROLLER DESIGN

The foundation of a fuzzy logic controller structure is a fuzzy set, in which a variable belongs to one or more sets with a given degree of membership. Using fuzzy logic has several advantages, including the ability to quantify ambiguous information, simulate human reasoning in computers, and generate decision based on unclear information, like the PV module's resistive load through

the DC-DC converter. Designing a fuzzy logic controller involves the main steps; Fuzzification, Fuzzy Interference and Defuzzification.

Fuzzification:

Fuzzification is the process of converting crisp or precise input data into fuzzy sets. In the real world, many variables are not simply "true" or "false" but exist on a continuum. Fuzzy sets allow us to represent this continuum of possibilities. The input data is mapped to fuzzy sets using membership functions, which assign a degree of membership to each input value for various fuzzy sets. These membership functions determine how well an input value belongs to each fuzzy set. Fuzzification is the first step in converting numerical data into a form that can be processed by a fuzzy inference system [80].

Fuzzy Inference:

Fuzzy inference is the heart of a fuzzy logic system. It is the process of using fuzzy rules to make decisions or draw conclusions based on the fuzzy sets obtained from the fuzzification step. Fuzzy rules typically take the form of "If-Then" statements and are expressed in terms of linguistic variables and fuzzy sets. The fuzzy inference engine combines these rules and input values to determine the degree to which each rule is satisfied. It then combines the consequences of these rules to produce a fuzzy output. There are various methods for performing fuzzy inference, including Mamdani and Sugeno models, which use different techniques to combine rule outputs.

Defuzzification:

Defuzzification is the process of converting the fuzzy output from the inference engine back into a crisp value or a single, definite result. In many practical applications, a crisp output is required

for decision-making or control. There are several methods for defuzzification, and the choice of method depends on the specific application. Common defuzzification methods include the centroid method (also known as the centre of gravity method), the maxima method, and the weighted average method. These methods consider the distribution of the membership function of the fuzzy output to determine a single, representative crisp value

5.2.1. Membership functions of proposed FLC

The fuzzy sets for the inputs and outputs are defined as shown in figure 5-1 to figure 5-4. Five fuzzy subsets; negative small(NS), negative medium(NM), negative big(NB), zero, positive small(PS), positive medium(PM), postive big (PB) were selected for the input and out variables of the FLC

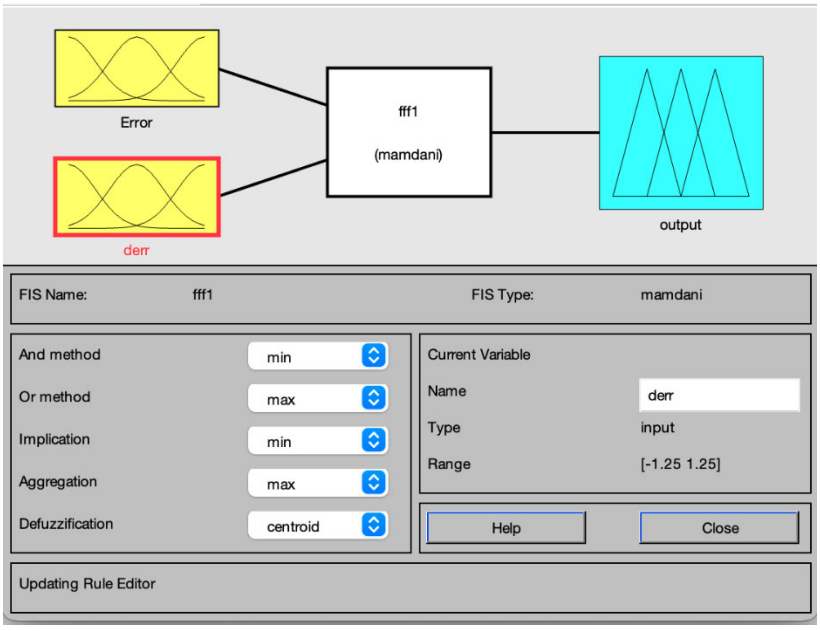

Figure 5-1: FLC designer in MATLAB toolbox

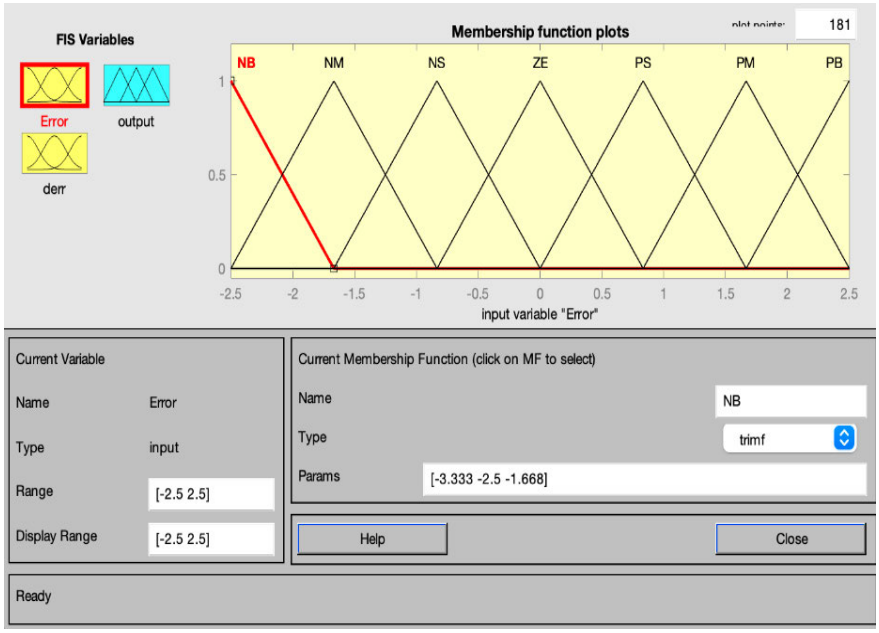

Figure 5-2: Membership functions for input error

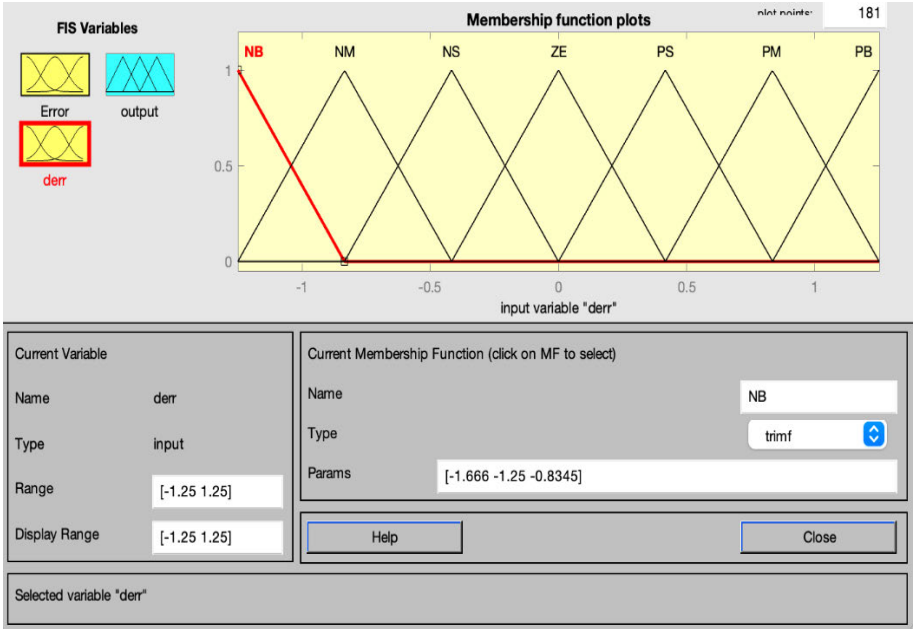

Figure 5-3: Membership functions for change in error

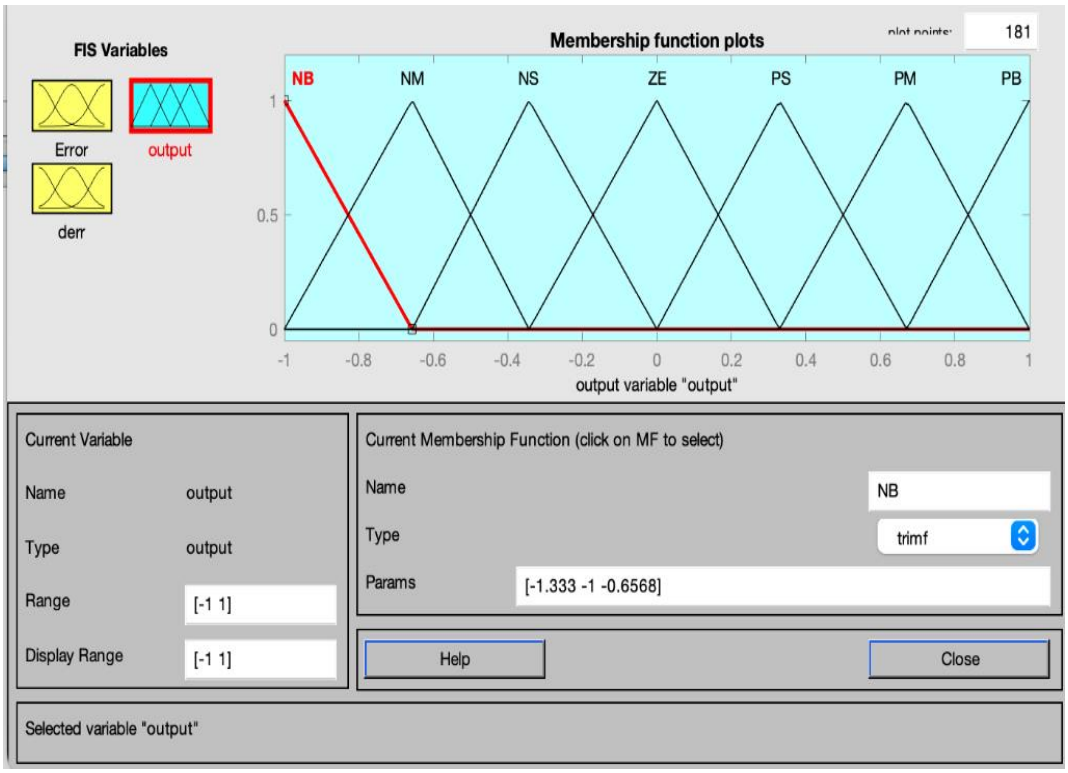

Figure 5-4: Membership functions for the output

5.2.2. Control rules for proposed FLC

Figure 5-5 and Figure 5-6 shows the IF statements as programmed in MATLAB and Table 5-1 shows the rules based on the membership functions in figure 5-1.

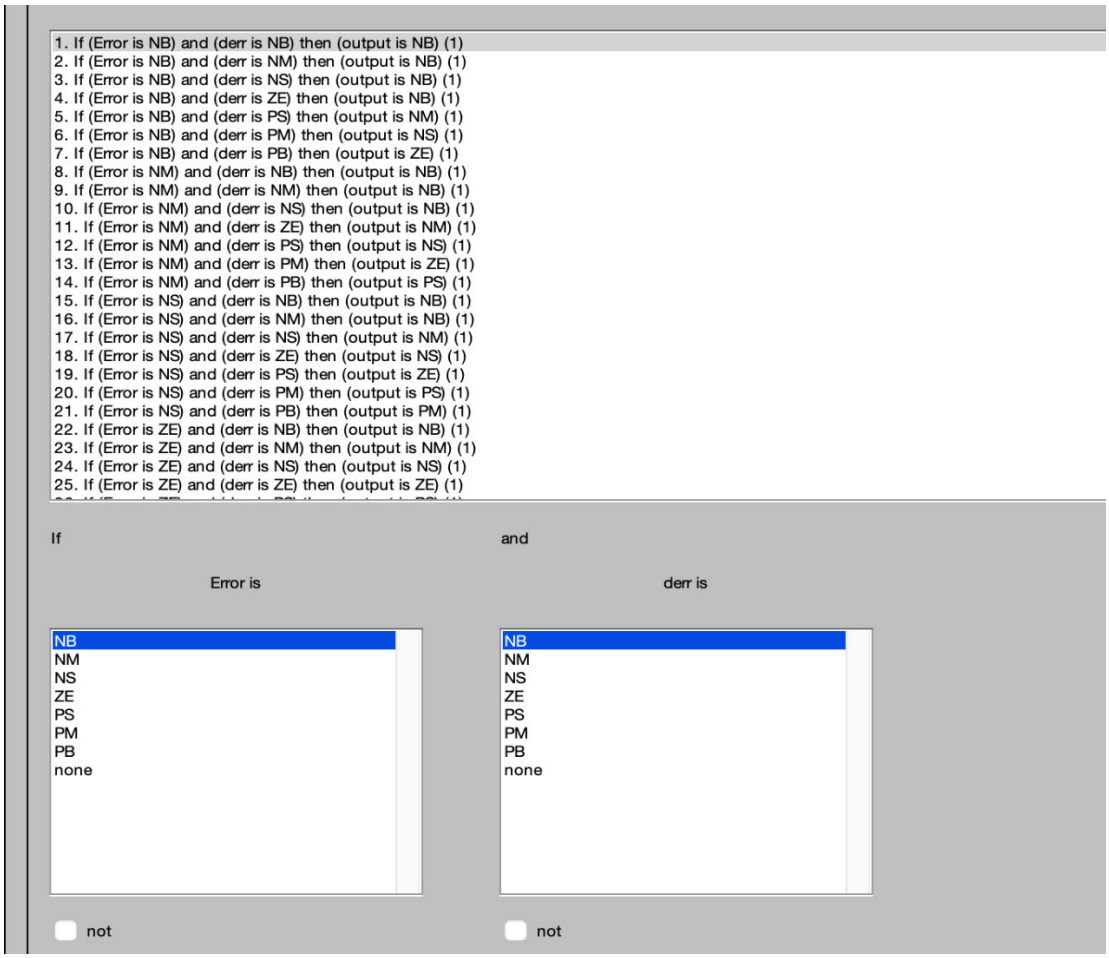

Figure 5-5: IF statements for proposed FLC (Rules 1-25)

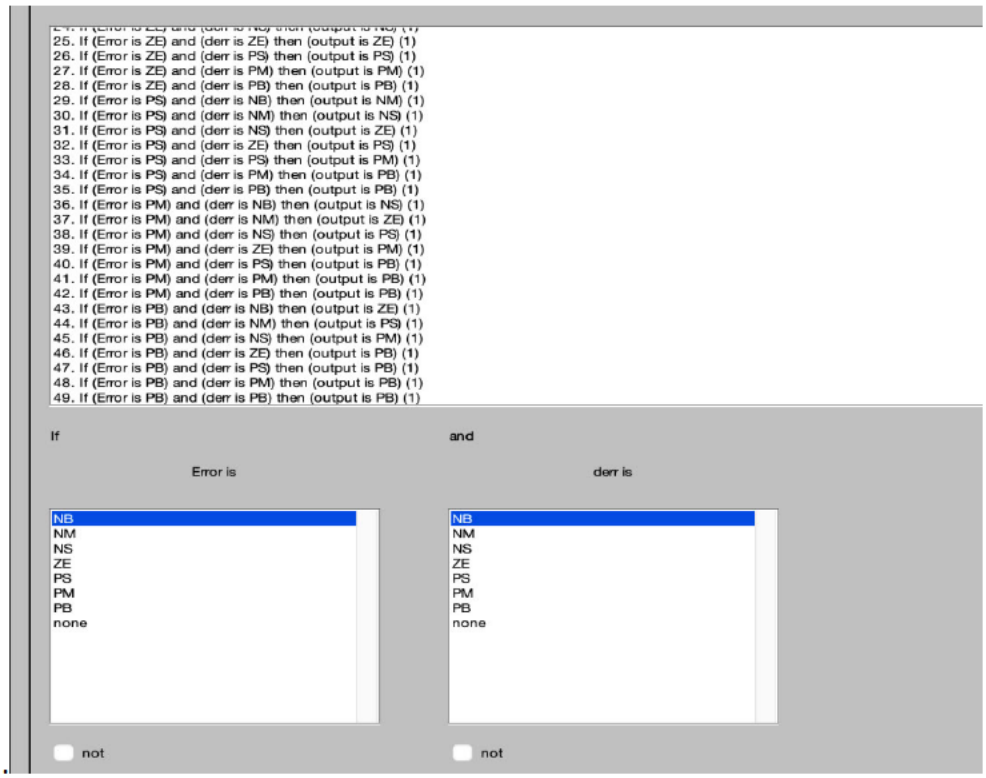

Figure 5-6: IF statements for proposed FLC (Rules 26-49)

Table 5-1: Rules based on Membership functions.

ERROR/DERROR	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Figure 5-7 shows the graphical representation of the rule base which is the FLC rule surface. The ruler view of the FLC is shown in figure 5-8 and this indicates the FLC during the change of inputs.

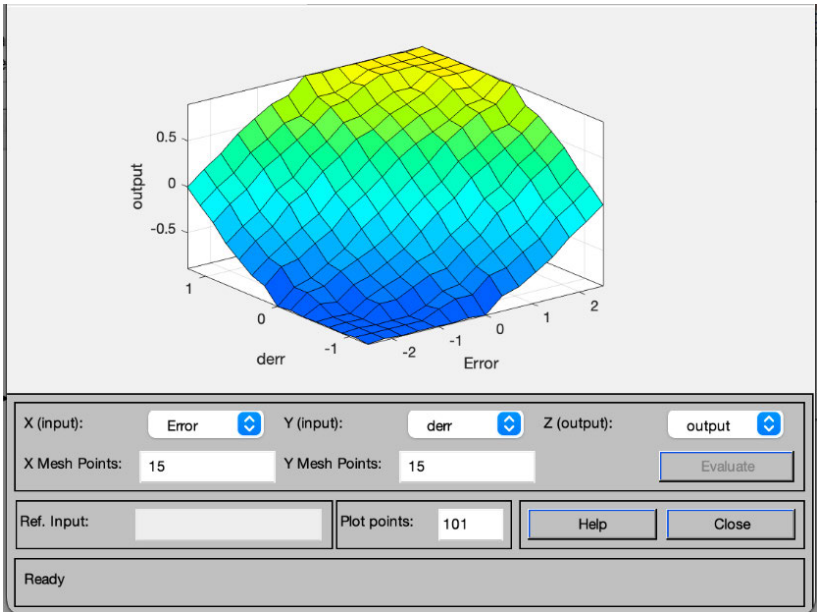

Figure 5-7: Rule surface for proposed FLC

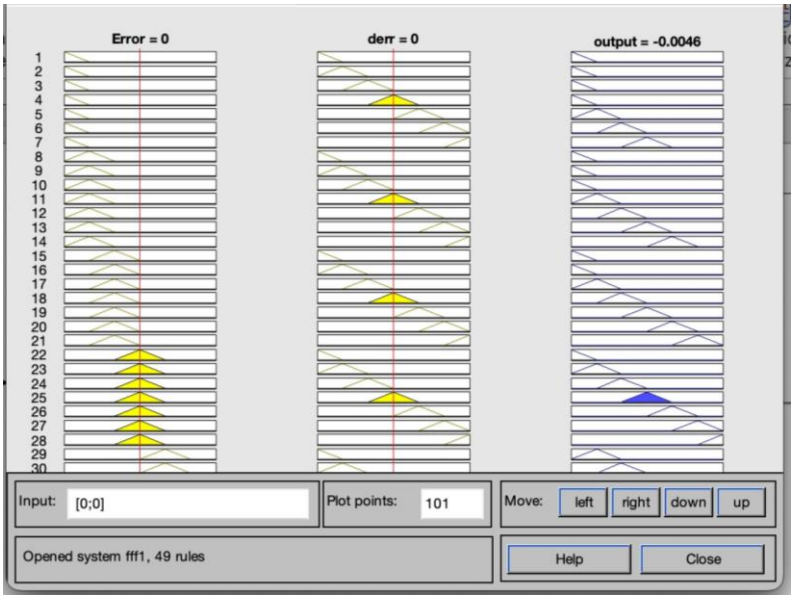

Figure 5-8: Ruler view of proposed FLC

5.3. SIMULINK MODEL OF HYBRID PV-FUEL SYSTEM WITH FLC

Figure 5-9 below shows the MATLAB/Simulink model of the hybrid PV-Fuel cell system with a FLC. The MIMO converter design follows the design that was discussed in chapter 3.

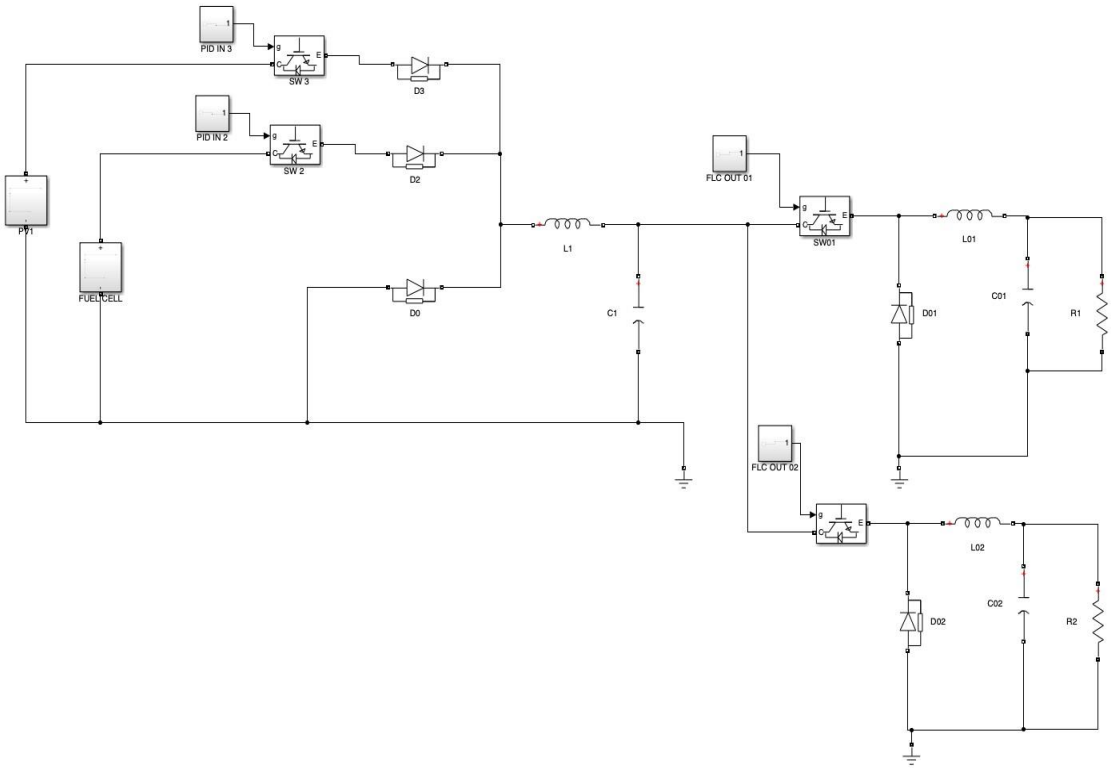

Figure 5-9: Proposed Hybrid PV-fuel cell system

5.4. SIMULATION RESULTS

5.4.1. Simulation Results

In this section, performance of the converter was tested with two different controllers: Integral Controller and a FLC against a hybrid PV-Fuel cell system under varying conditions. Figure 5-10 shows the simulations results where the converter was controlled by a FLC and the Fuel cell and PV operating at maximum capacity which is 350V and 400V respectively. The desired outputs are V_{01}=110V and V_{02}=48V. Figure 5-11 shows the simulations results under the same conditions as figure 5-6 with the converter being controlled with a I-controller.

Figure 5-8 shows the simulations results where the converter was controlled by a FLC and the Fuel cell and PV are operating at 50% capacity which is 175V and 200V respectively. The desired outputs are V_{01}=110V and V_{02}=48V. Figure 5-12 shows the simulations results under the same conditions as figure 5-13 with the converter being controlled with a I-controller.

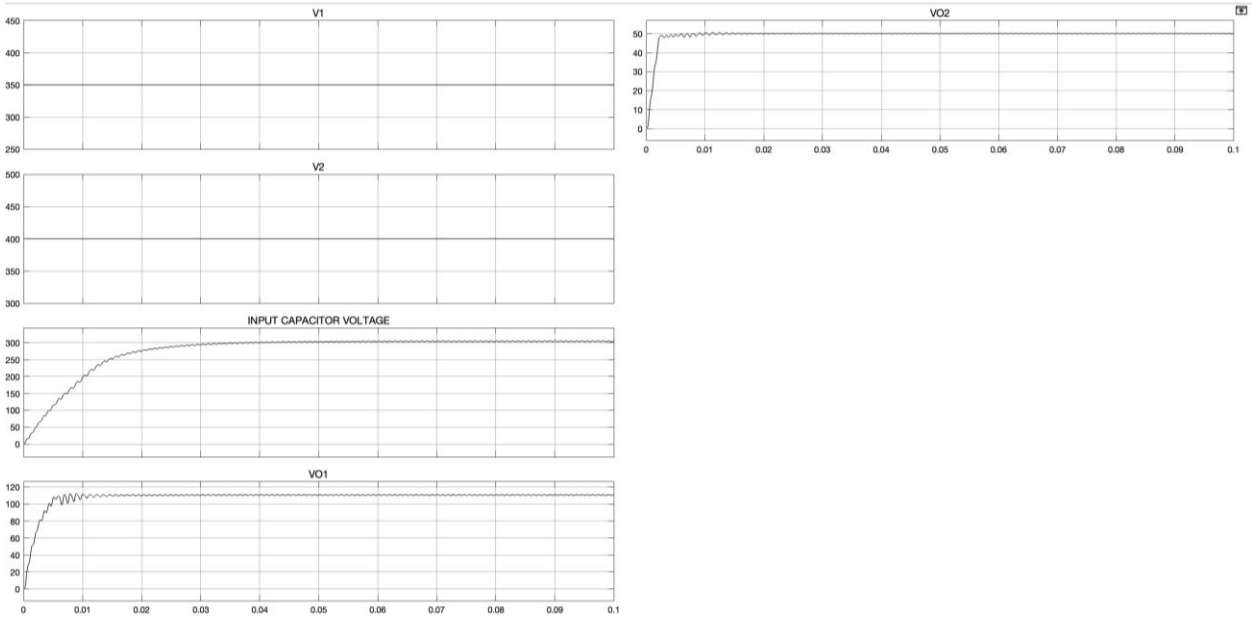

Figure 5-10: FLC controlled MIMO converter at maximum input voltage capacity.

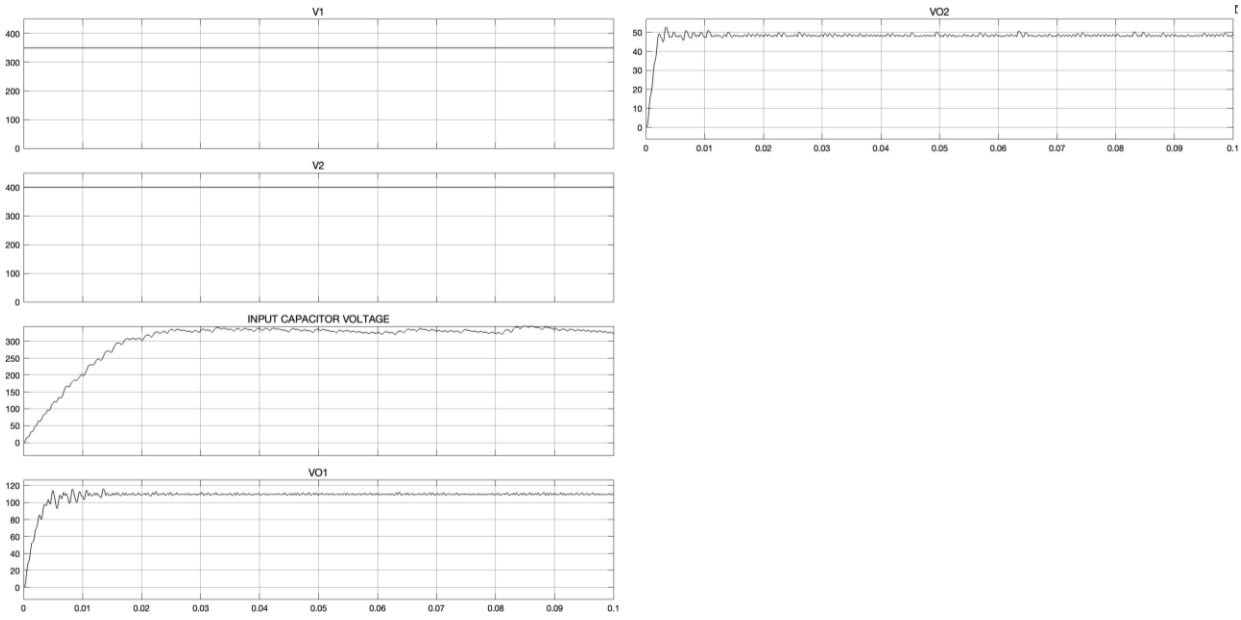

Figure 5-11: I-controller controlled MIMO converter at maximum input voltage capacity.

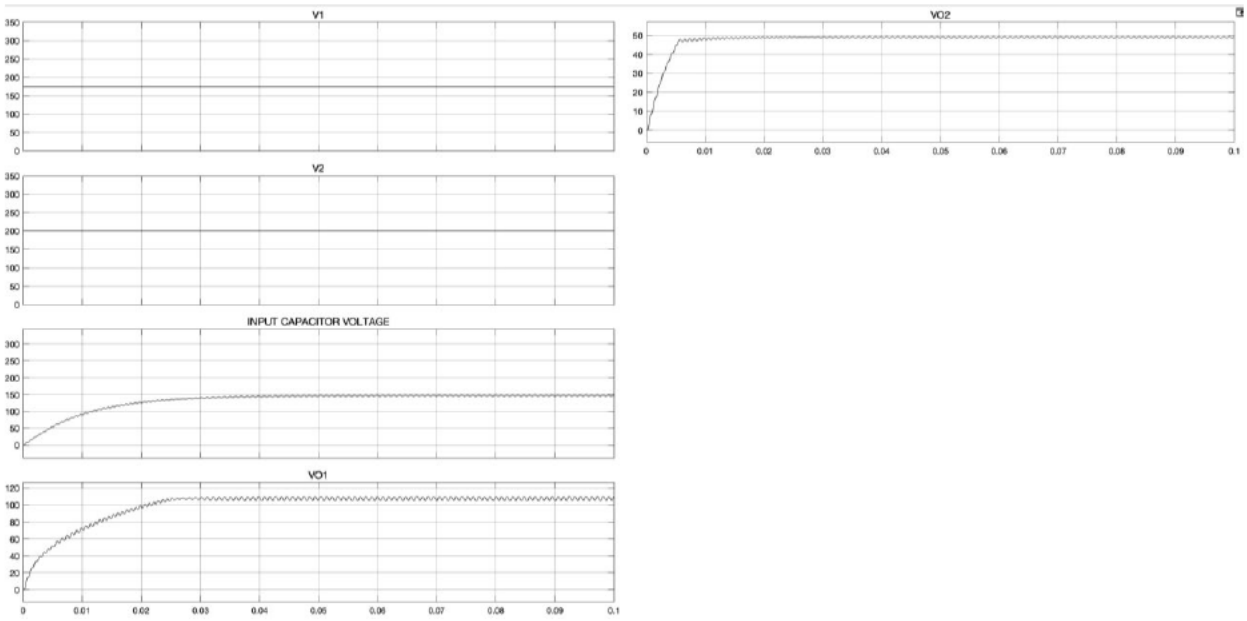

Figure 5-12: FLC controlled MIMO converter at 50% of the maximum input voltage.

5.4.2. Comparative analysis of the transient response of FLC and PID controllers

Table 5-2: Transient response of FLC vs I-controller at maximum voltage capacity

PV=350V and FC = 400V					
Output Voltage V_{01}				**Output Voltage V_{02}**	
	With FLC	**With I-controller**		**With FLC**	**With I-controller**
Rise time	3.793ms	3.541ms	**Rise time**	1.616ms	1.506ms
Overshoot	1.531%	5.851%	**Overshoot**	0.090%	9.341%
Undershoot	10.676%	15.486%	**Undershoot**	4.686%	6.856%
Settling time	10.183ms	12.076ms	**Settling time**	9.662ms	17.860ms

Table 5-3: Transient response of FLC vs I-controller at 50% voltage capacity

PV=175V and FC = 200V					
Output Voltage V_{01}				**Output Voltage V_{02}**	
	With FLC	**With I-controller**		**With FLC**	**With I-controller**
Rise time	15.751ms	14.537ms	**Rise time**	4.333ms	4.022ms
Overshoot	0.942%	4.677%	**Overshoot**	0.142%	5.851%
Undershoot	7.847%	11.917%	**Undershoot**	4.706%	7.495%
Settling time	19.791ms	19.7036ms	**Settling time**	13.272ms	19.007ms

5.5. DISCUSSION OF RESULTS

This comparative analysis has demonstrated the superior performance of the fuzzy logic controller over the integral controller in the context of this specific hybridized system. The advantages of the fuzzy logic controller are evident when analyzing the transient response of the system. In all cases the FLC demonstrated very minimal overshoot and undershoots, far less than that of the I-controller. The FLC also has a shorter settling time, as compared to the I-controller.

The integral controller, while it performed relatively well it struggled to contend with the intricacies of systems characterized by nonlinear dynamics, uncertainties, and imprecise input data. Its inherent reliance on mathematical models and fixed control parameters makes it less versatile and often unable to effectively adapt to changing operating conditions.

On the other hand, the fuzzy logic controller has exhibited remarkable capabilities in handling the challenges posed by the proposed dynamic system. By incorporating linguistic variables and fuzzy rules, it can effectively capture the system's behavior and make decisions based on real-time, imprecise, and uncertain data. This adaptability is particularly beneficial in scenarios where traditional control methods fall short.

5.6. CONCLUSION

In this chapter, an investigation into the performance of the MIMO Converter within a hybridized PV-Fuel Cell system was conducted. The analysis included a comparative assessment of the converters performance against two control strategies: a fuzzy logic controller (FLC) and an integral controller and under maximum input voltages and 50% input voltage.

The chapter began by detailing the design and implementation of the FLC, which involved the critical stages of fuzzification, fuzzy inference, and defuzzification. The FLC was meticulously developed using MATLAB, showcasing the membership functions, rule surfaces, and rule views.

Subsequently, the simulations were carried out within the MATLAB Simulink environment to observe the behavior of the MIMO Converter under varying conditions. Specifically, the simulations provided insights into the input and output voltages. Furthermore, the transient responses of the system, comparing the performance of the fuzzy logic controller to that of the integral controller was examined. Notably, the findings clearly demonstrated that the fuzzy logic controller consistently outperformed the integral controller in achieving superior control outcomes.

CHAPTER 6

CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

6.1. CONCLUSION

Chapter 3 of this study proposed a multiple input and multiple out DC-DC converter model that is intended for low to high voltage applications. The converter boasts a simple configuration, fewer components, and a high conversion ratio. To support the claims made about the converter's performance, mathematical models for both ideal and non-ideal conditions were developed and the converter's operation principles and switching states were explained. Chapter 4 and 5 presented simulations in MATLAB/SIMULINK to validate the design, and the results showed that the converter is flexible and reliable, with the controller automatically adjusting power switches to maintain a constant output voltage as supply or demand changes.

Additionally, the research delved into the assessment of the proposed converter within a hybridized PV-Fuel cell system. This evaluation involved subjecting the converter to scrutiny under two distinct control strategies: fuzzy logic control and integral control. Unlike the integral controller, which relies on mathematical models and fixed parameters, the fuzzy logic controller's linguistic variables and fuzzy rules make it highly adaptable to changing operating conditions. This adaptability, coupled with its transparency and simplicity in knowledge representation, reduces development time and effort, making it an ideal choice for addressing control challenges in modern engineering and automation systems. The results of this study underscore the growing significance

of fuzzy logic controllers in a wide range of industries and applications where precision and adaptability are essential for superior control performance.

Overall, the study presents a converter which focuses more on supply coordination which has several advantages, including optimized structure, lower component count, and good efficiency. The converter is versatile and can integrate multiple input sources to enable energy diversification from different sources individually or simultaneously, even under intermittent conditions. The converter's compact design and flexibility make it an attractive option for many applications. Its simplicity, reliability, and performance suggest it could have a significant impact on marine renewable energy integration, microgrid, hybrid electric vehicle applications, ultracapacitor enhancement battery packs, hybrid photovoltaic or fuel cell systems, distribution generation, battery charging stations and where energy storage systems and energy sources with different power characteristics need to be combined.

The research provides evidence that the converter's use can enhance the reliability and performance of energy conversion and distribution systems. In summary, the proposed converter represents an effective solution for energy diversification, and its successful simulation results suggest it could be an asset to the energy industry.

6.2. MAIN CONTRIBUTION

- This dissertation has provided a review of multiple input, multiple output power converter topologies and control strategies
- Mathematical modelling is used to analyze and optimize the system performance
- A MATLAB/Simulink model for a multi-input multi-output DC-DC converter is developed.

- A MATLAB/Simulink model for a dual input PV-Fuel Cell system is developed
- The study investigated two control strategies in the form of PID control and FLC control for the coordinated operation of a multi-input, multi-output (MIMO) converter to enhance supply coordination.

6.3. FUTURE STUDY

- Researchers can examine cutting-edge control strategies like model predictive control, and sliding mode control and evaluate how well they function in comparison to conventional control strategies.
- Researchers can also look at optimization techniques such as genetic algorithms and particle swarm optimization, to find the best optimal control parameters

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