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CENTER OF TECHNOLOGY
POSTGRADUATE PROGRAM IN ELECTRICAL ENGINEERING

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MPPT for Photovoltaic Systems using Fractional Power Processing Architecture

Vitória, ES

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Master's Dissertation presented to the Postgraduate Program in Electrical Engineering at the Federal University of Espírito Santo, as a partial requirement for obtaining the Master's Degree in Electrical Engineering.

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Supervisor Prof. Dr. Walbermark Marques dos Santos

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STATEMENT OF AUTHORSHIP

I hereby declare that the thesis submitted is my own work. All direct or indirect sources used are acknowledged as references. I further declare that I have not submitted this thesis at any other institution in order to obtain a degree.

To the Brazilian people, who fund education and research in this country.

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"Education is the only way for a person to become emancipated."

Leonel Brizola

Resumo

Este estudo apresenta uma nova investigação, com contribuições conceituais, sobre como uma arquitetura de processamento fracionário de potência (FRPP) pode ser usada para rastrear o ponto de máxima potência de um sistema fotovoltaico (PV) utilizando módulos PV como fonte auxiliar.

Duas configurações são propostas para o processamento fracionário de potência dentro do sistema fotovoltaico. A primeira, denominada FRPP acoplado (CFRPP), utiliza apenas módulos fotovoltaicos como fonte auxiliar de energia, com conexão direta a um conversor. A segunda, denominada FRPP desacoplado (DFRPP), incorpora um sistema de armazenamento de energia (ESS) junto aos módulos PV, permitindo que os dois conjuntos PV funcionem de forma independente.

Simulações foram conduzidas para validar a análise teórica de um sistema PV sob essas duas configurações de arquitetura FRPP e comparar seu desempenho com diferentes arquiteturas de processamento de potência. Os resultados indicam que as equações de modelagem propostas são válidas.

Conclui-se que o processamento fracionário de potência permite que conversores projetados para níveis de potência mais baixos regulem a geração de níveis mais altos. Quando aplicados a sistemas fotovoltaicos, ambos os tipos de FRPP demonstraram a capacidade de atingir a potência máxima utilizando conversores de baixa potência e baixa complexidade, uma vez que não são isolados e podem até adotar topologias simples, como buck ou boost. No entanto, cada tipo apresentou capacidades significativamente diferentes.

A configuração DFRPP demonstra sua viabilidade ao oferecer desempenho superior em comparação com outras arquiteturas de processamento de energia. Em contraste, a arquitetura CFRPP apresenta limitações de desempenho, tornando-a menos vantajosa quando comparada a outras.

Palavras-chaves: processamento fracionário de potência, processamento parcial de potência, multi-fonte, sistemas fotovoltaicos.

Abstract

This study presents a novel investigation, with conceptual contributions, into how a fractional power processing (FRPP) architecture can be used to track the maximum power point of a photovoltaic (PV) system while using PV modules as the auxiliary source.

Two configurations are proposed for fractional power processing within the photovoltaic system. The first, referred to as coupled FRPP (CFRPP), utilizes only photovoltaic modules as the auxiliary energy source, with direct connection to a converter. The second, referred to as decoupled FRPP (DFRPP), incorporates an energy storage system (ESS) alongside the PV modules, allowing the two PV arrays to function independently.

Simulations were conducted to validate the theoretical analysis of a PV system under these two FRPP architecture configurations and to compare their performance to different power processing architectures. The results indicate that the proposed model equations are valid.

It is concluded that fractional power processing enables converters designed for lower power levels to regulate the generation of higher. When applied to photovoltaic systems, both types of FRPP have demonstrated the ability to achieve maximum power while using low-power, low-complexity converters, since they are non-isolated and can even adopt simple topologies, such as buck or boost. However, each type exhibited significantly different capabilities.

The DFRPP configuration demonstrates its viability by delivering superior performance compared to other power processing architectures. In contrast, the CFRPP architecture exhibits performance limitations, making it less advantageous under comparable conditions.

Keywords: fractional power processing, partial power processing, multi-source, PV systems.

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List of abbreviations and acronyms

CFRPP	Coupled Fractional Power Processing
CMPPT	Centralized Maximum Power Point Tracking
DC	Direct Current
DFRPP	Decoupled Fractional Power Processing
DMPPT	Distributed Maximum Power Point Tracking
DPC	Differential Power Converter
DPP	Differential Power Processing
ESS	Energy Storage System
FPC	Full Power Converter
FPP	Full Power Processing
FRPC	Fractional Power Converter
FRPP	Fractional Power Processing
I-V	Current-voltage
MAE	Mean Absolute Error
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NoPP	No Power Processing
P&O	Perturb and Observe
PPC	Partial Power Converter
PPP	Partial Power Processing
P-PPC	Parallel-connected Partial-Power Converter
PV	Photovoltaic
P-V	Power-voltage
STC	Standard Test Conditions
S-PPC	Series-connected Partial-Power Converter

List of symbols

β	Auxiliary-battery factor
ΔD	Duty cycle step
ΔV_{mpp}	Main string operating voltage range
$\Delta V_{mpp \ max}$	Main string maximum operating voltage range
$\Delta V_{mpp \ ref}$	Main string reference operating voltage range
η_c	Efficiency of the converter, in the CFRPP architecture
η_{c1}	Efficiency of the first converter, in the DFRPP architecture
η_{c2}	Efficiency of the second converter, in the DFRPP architecture
μ	Auxiliary-source factor
ρ_{cfrpp}	Overall performance of a CFRPP system
ρ_{dfrpp}	Overall performance of a DFRPP system
ρ_{fpp}	Overall performance of a FPP system
ρ_{syst}	Overall performance of the first stage of a PV system
ρ_{nopp}	Overall performance of a NoPP system
ρ_{ref}	Reference performance value
D	Duty cycle unified control variable
D_{boost}	Duty cycle for boost mode
D_{buck}	Duty cycle for buck mode
f	Processed power ratio
G	Static gain
I_{mpp}	Maximum power point current
I_{str}	Main string current
m	number of PV components in auxiliary string

n	number of PV components in main string
N	number of all PV components in a string
P_{bat}	Auxiliary battery power
P_{bus}	DC-bus power
P_c	Auxiliary source power
P_m	Auxiliary string operating power
P_{mpp}	Maximum available photovoltaic power
P_n	Main string operating power
r	Main-to-auxiliary components ratio
V_{bat}	Auxiliary battery voltage
V_{bus}	DC-bus voltage
V_c	Auxiliary source voltage
V_m	Auxiliary PV string operating voltage
V_{mpp}	PV maximum power point voltage
$V_{mpp-high}$	Highest value of PV maximum power point voltage
$V_{mpp-low}$	Lowest value of PV maximum power point voltage
$V_{mpp-mean}$	Mean value of PV maximum power point voltage
V_n	Main PV string operating voltage

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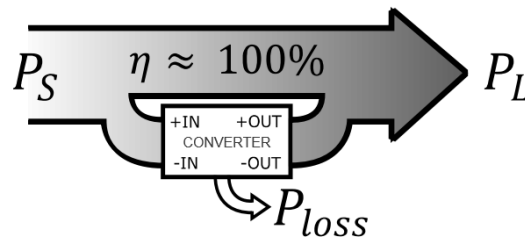
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1 Introduction

Partial Power Processing (PPP) is a topic of study that focuses on improving the performance of power electronics systems by processing only a portion of the total generated power. The core idea behind PPP is to use a converter that process just enough power to control the source operation point, allowing the rest of it to flow directly to the load without passing through the converter, as illustrated in Figure 1. This approach reduces power losses and, consequently, improves system efficiency.

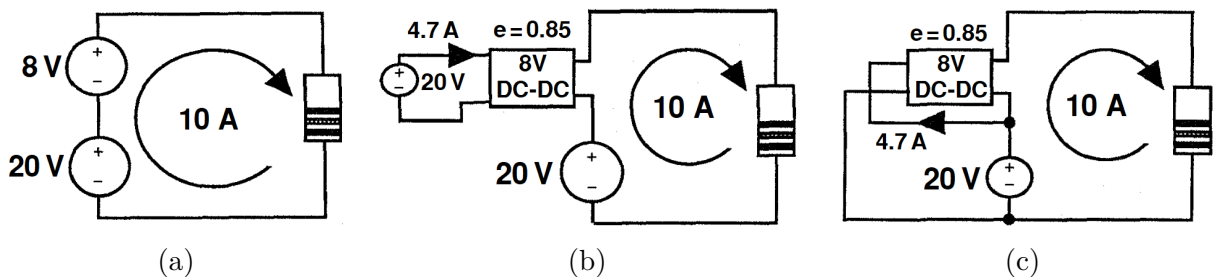
Figure 1 – Power flow diagram for PPP: P_S = source power; P_L = load power; P_{loss} = losses



Source: Modified from [Anzola et al. \(2020\)](#)

As suggested by [Zientarski et al. \(2017\)](#), PPP is a concept introduced in [Enslin and Snyman \(1991\)](#) to control battery charging and discharging in isolated photovoltaic generation systems. In [Button \(1996\)](#), it was proposed as an alternative for NASA spacecraft power systems. Figure 2 illustrate how the concept of partial power processing was originally conceived by [Button \(1996\)](#). Initially, Button considers two separate DC sources powering the load (Figure 2a). Then, the lower-voltage source (8 V) is replaced by one with the same value as the other (20 V), with a DC-DC converter reducing its voltage to match that of the former source (Figure 2b). Finally, he proposes that, instead of using two separate sources of equal voltage, the same source could be used for both functions (Figure 2c), by connecting it in parallel with the converter input and in series with the output.

Figure 2 – Partial power processing conception.

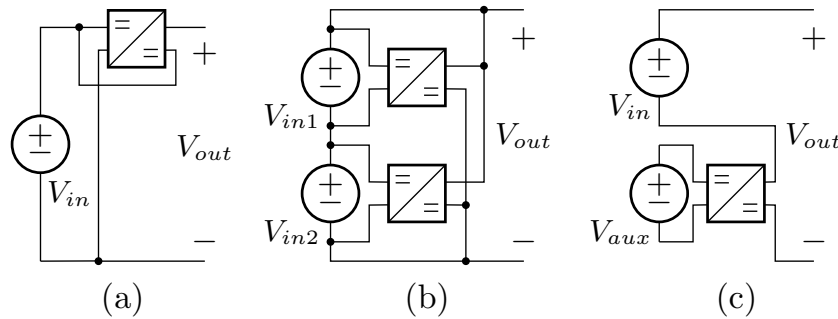


Source: Modified from [Button \(1996\)](#)

As research on this topic has evolved, various architectures have been proposed to achieve partial power processing. Some authors, such as [Kwon et al. \(2022\)](#) and [Xue, Yu and Huang \(2020\)](#), categorize PPP into three fundamental types, illustrated in Figure 3:

- a) Partial Power Converter (PPC): a converter applied to a single power source that is connected at both the input and the output, allowing part of the power to flow directly to the load. This configuration employs series regulation to control the output voltage.
- b) Differential Power Converter (DPC): converters designed to compensate for power imbalances between series-connected sources by processing only the power difference between them. This configuration employs parallel regulation to independently control the current in each source.
- c) Fractional Power Converter (FRPC): a converter that requires an auxiliary power source to control the main power source. This configuration employs series regulation to control the output voltage.

Figure 3 – Examples of different types of partial power processing: (a) Partial. (b) Differential. (c) Fractional.



Source: Author

It is possible to find some discrepancies in the literature regarding nomenclature. The architecture featuring an auxiliary power source, depicted in Figure 3c, will be referred to as “fractional power processing” (FRPP) in this work. Other studies, such as [Anzola et al. \(2020\)](#) and [Gsous et al. \(2024\)](#), classify this architecture differently, referring to it as a “multi-source converter”, which they consider part of a “mixed PPP architecture”. They use the term “fractional” exclusively to refer to a specific type of converter connection, as proposed in [Mira et al. \(2019\)](#). These discrepancies will be examined and discussed in Section 1.2.

By comparing Figure 3a with Figure 2a, and Figure 3c with Figure 2c, it is evident that FRPP was conceived alongside PPC and, consequently, sharing some characteristics—such as series regulation, since the load voltage is obtained by summing the main

source voltage and the converter’s output voltage. Despite this, PPC has been more widely discussed in the literature, likely due to the advantage of using a single source. However, one drawback lies in its dependence on converter topology to ensure that switches and passive elements effectively process only a fraction of the total power—a topic that will be examined in more detail in Sections 1.1 and 1.2.

1.1 Problem Contextualization

Partial power processing is particularly relevant in photovoltaic (PV) applications, since it offers the possibility to improve the global efficiency of PV systems and reduce the cost and size of the MPPT DC-DC converters (Kwon et al., 2022).

The topologies used as PPC can be used as a full power processing converter (FPC) as well. The core difference of a PPC is the unorthodox interconnections between source, load, and the converter terminals that change the traditional power flow on the components, often reducing their stress and requiring smaller sizing. However, depending on the converter topology, some configurations are unable to PPP. Moreover, certain configurations that do reduce active power may also increase non-active and total power processed, resulting in no reduction in component sizing or improvement in system efficiency, as shown in Zientarski et al. (2015), Zientarski et al. (2017) and Zientarski et al. (2018).

On the other hand, fractional power processing employs a full power converter (FPC) with an separate auxiliary source that is connected in such a way that it is able to control the main source, which in turn will generate power without processing. Since it uses an FPC, with ordinary terminal connections, the expected power flow on the converter’s components will be the same as in a traditional application, with no risk of increasing the amount of total power processed.

Thus, applying the FRPP architecture to photovoltaic systems may offer a viable solution for enabling the use of simple, non-isolated converters—such as buck and boost—while still achieving benefits in component sizing reduction and overall efficiency improvement.

1.2 Literature Review

Enslin and Snyman (1991) is the earliest study identified in this literature review that applies the PPP concept. In it, the authors present a battery charger for stand-alone PV power systems—designed to perform MPPT—with a specific connection they claim allows part of the power from the PV generator to flow directly to the battery.

Button (1996) introduces for the first time the architecture now known as S-PPC IPOS (Series connected-Partial Power Converter Input-Parallel Output-Series), as

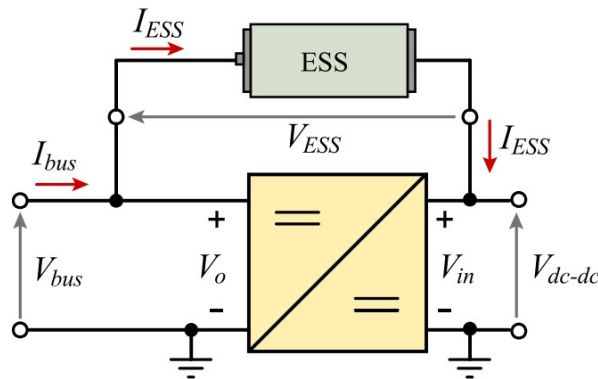
illustrated in Figure 2c, which has since been widely disseminated in the literature. This work also proposes the application of PPP to photovoltaic systems.

Although partial PPP was introduced nearly 30 years ago, it remains a subject of ongoing debate within the academic community. For instance, [Suntio and Kuperman \(2014\)](#) identifies flaws in the theoretical analysis presented by [Agamy et al. \(2013\)](#). Additionally, [Zhao, Yeates and Han \(2013\)](#) asserts that S-PPC cannot be implemented using non-isolated topologies, as certain configurations may cause a short circuit at the input source—depending on the PPC configuration—or result in an electrical arrangement equivalent to FPC, thereby forfeiting the benefits of partial processing. In contrast, the FRPP architecture—which also uses series regulation—avoids direct connections between input and output terminals, making it more compatible with non-isolated topologies.

The doctoral thesis by [Zientarski et al. \(2017\)](#), written in Portuguese, aims to deepen the understanding of PPP concepts. The work notably emphasizes that processing only the active power component does not necessarily lead to a reduction in the total power processed by the converter. To address this, the author proposes a method for calculating non-active power in order to determine whether a converter truly achieves PPP. The contributions presented in the thesis are also available in English through the articles [Zientarski et al. \(2015\)](#), [Zientarski et al. \(2017\)](#), and [Zientarski et al. \(2018\)](#).

[Mira, Zhang and Andersen \(2018\)](#) and [Mira et al. \(2019\)](#) introduced a new power processing configuration termed the “fractional converter”, illustrated in Figure 4, which was claimed to be compatible with non-isolated topologies. However, this concept bears no relation to the FRPP architecture discussed herein. Subsequently, [Anzola et al. \(2022\)](#) analyzed this configuration and concluded that it does not achieve PPP when implemented with a conventional single-inductor topology, achieving PPP only when a dual-inductor topology is employed.

Figure 4 – Fractional Charging Converter, according to [Mira et al. \(2019\)](#)

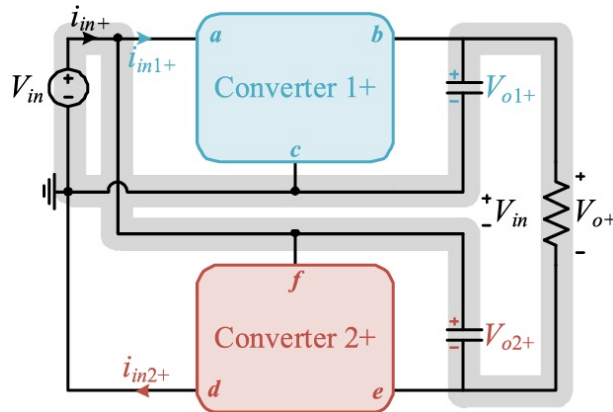


Source: [Mira et al. \(2019\)](#)

Another power processing configuration that appears to be compatible with non-isolated topologies is the one based on “differential connections”—which bears no relation

to the DPC—presented in [Andrade, Coelho and Lazzarin \(2022\)](#) and [Andrade, Coelho and Lazzarin \(2024\)](#) and illustrated in Figure 5. It uses two converters with input terminals connected in parallel with the source, and the load is connected to one of the terminals of each converter. However, no further analyses were found to ascertain PPP in this configuration, especially using the method proposed in [Zientarski et al. \(2017\)](#).

Figure 5 – Example of partial power processing configuration based on “differential connections”



Source: [Andrade, Coelho and Lazzarin \(2022\)](#)

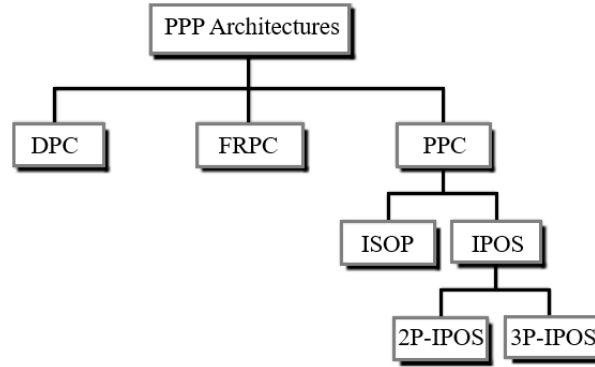
Several studies have addressed the use of PPC and DPC in PV systems, including [Kasper, Bortis and Kolar \(2013\)](#), [Ahmad and Anand \(2016\)](#), and [Li and Cobos \(2021\)](#), whereas research on FRPP remains limited. For instance, [Tsuruta and Kawamura \(2015\)](#) presents an FRPP architecture for battery charging but refers to the converter as PPC. Similarly, [Xue, Yu and Huang \(2017\)](#) applies FRPP to battery systems and introduces the term “fractional power converter” to describe the architecture, yet uses PPC terminology interchangeably. In [Xue, Yu and Huang \(2020\)](#), the author revisits FRPP in the context of battery charging and clarifies the distinction, formally differentiating PPC from FRPC—the latter denoting the converter used in FRPP.

[Kim and Parkhideh \(2018a\)](#) and [Kim and Parkhideh \(2018b\)](#) propose a configuration similar to FRPP, applied to PV systems, in which the battery is treated as an auxiliary source. However, in their design, the battery is connected in series with the PV module, which is then linked to a DC bus. The converter connects the battery to the bus. This setup differs from the FRPP architecture, as the converter output in FRPP is placed in parallel with both the PV array and the auxiliary source. In [Kim, Roy and Parkhideh \(2021\)](#), the authors revisit the configuration, introducing a capacitor between the PV module and the battery to allow the system to interface with a fixed DC bus.

[Kwon et al. \(2022\)](#) is the only study identified in this literature review that applies the FRPP architecture to photovoltaic systems. However, the analysis remains superficial, offering only an overview of the three types of power processing, classified in the same

manner as in [Xue, Yu and Huang \(2020\)](#), as illustrated in Figure 6.

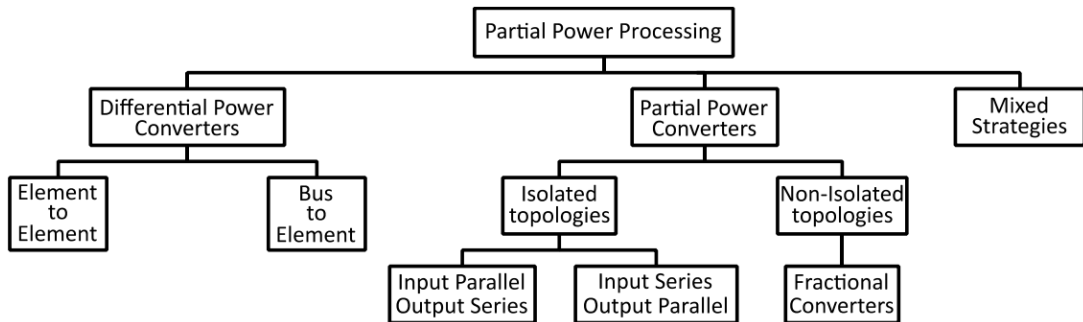
Figure 6 – Partial power processing types, according to [Kwon et al. \(2022\)](#)



Source: [Kwon et al. \(2022\)](#)

In terms of nomenclature, some review studies, such as [Anzola et al. \(2020\)](#) and [Gsous et al. \(2024\)](#), classify the FRPP differently, naming the architecture that requires an auxiliary power source a “multi-source converter”, one of what they call “mixed PPP architecture”, as illustrated in Figure 7. Additionally, they use the term “fractional converter” to describe the converter configuration proposed in [Mira et al. \(2019\)](#), which is unrelated to the FRPP discussed in this work. Notably, the review by [Santos, Zientarski and Martins \(2021\)](#) does not reference FRPP.

Figure 7 – Partial power processing types, according to [Anzola et al. \(2020\)](#)



Source: [Anzola et al. \(2020\)](#)

In this document, the architecture with an auxiliary power source, illustrated in Figure 3c, will be referred to as “fractional power processing”, while the term “fractional converter” will be reserved for the configuration proposed in [Mira et al. \(2019\)](#), shown in Figure 4. This distinction is made because the converter used in an FRPP architecture exhibits no unique characteristics and follows a conventional configuration—the same as a FPC—without a direct connection between input and output terminals. The notion of processing only a fraction of the system’s energy is not inherent to the converter itself, but arises from the broader architecture, specifically in how this conventional FPC is integrated into the system.

1.3 Justification

The literature review revealed limited research on FRPP, particularly in the context of PV applications, as most studies focus on battery charging systems (Xue; Yu; Huang, 2020)(Tsuruta; Kawamura, 2015)(Xue; Yu; Huang, 2017). It also identified discrepancies in nomenclature and conceptual definitions.

Therefore, this study proposes a novel investigation into the functionality and limitations of FRPP architectures applied to PV systems—where some PV modules serve as auxiliary sources, with and without an energy storage system (ESS) used to decouple the auxiliary string from the rest of the array. No prior studies were identified that adopt this specific approach.

The two proposed architectures are introduced in Section 2.5: one without an ESS, referred to as “Coupled Fractional Power Processing” (CFRPP), investigated in Chapter 4; and one with an ESS, referred to as “Decoupled Fractional Power Processing” (DFRPP), explored in Chapter 5.

Simulations were performed to validate both theoretical models and to evaluate the performance of the proposed FRPP architectures against defined benchmark cases, with the aim of identifying suitable application scenarios.

1.4 Research Objectives

1.4.1 General Objective

The main objective of this work is to verify the feasibility of using fractional power processing as an MPPT method for photovoltaic systems, employing photovoltaic components (cell, sub-modules, modules...) as both the main and auxiliary sources.

1.4.2 Specific Objectives

- Conduct a bibliographic review of works that discuss fractional power processing, highlighting the conceptual differences in how FRPP is interpreted or implemented.
- Determine the mathematical equations that define the operation of the Fractional Power Processing Architecture as a maximum power point tracking method for photovoltaic systems.
- Validate the proposed theoretical model through the application of computer-based simulations.
- Evaluate the performance of different types of Fractional Power Processing Architectures in comparison to other power processing architectures.

1.5 Document Organization

This dissertation is organized into six chapters.

Chapter 1 provides an overview of the basic concepts related to partial power processing and its main paradigms. It also includes a bibliographic review of fractional power processing, highlighting the lack of studies in the literature regarding this architecture when applied to photovoltaic systems. Based on this, the justification and objectives of the research are presented.

Chapter 2 reviews various types of power processing architectures, explaining their operation, limitations, and capabilities.

Chapter 3 details the methodology adopted to evaluate the proposed architectures as MPPT methods for photovoltaic systems. It also defines benchmark architectures to serve as references for performance comparison.

Chapter 4 introduces the first architecture proposed in this dissertation: Coupled Fractional Power Processing. Its operation is described, mathematical models are developed to characterize its limitations and capabilities. The theoretical analysis is complemented by the validation of the mathematical model through computational simulation. The architecture's performance is then evaluated and compared to the benchmark cases.

Chapter 5 presents the second proposed architecture: Decoupled Fractional Power Processing. It follows the same structure as Chapter 4, explained in the previous paragraph.

Chapter 6 contains the general conclusions and final considerations, along with proposals for future research directions.

2 Types of Power Processing Architectures

In photovoltaic systems, it is common to connect PV modules to loads that can be modeled as DC voltage sources—such as the DC bus of a microgrid, the input capacitor of a grid-tied inverter, or a battery bank.

This chapter presents architectures designed to connect PV modules to the DC voltage source and extract power from the PV array—ideally, the maximum available power. Sections 2.1 and 2.2 address two extremes of power processing: one where all PV power passes through one or more converters, and another where the PV power flows directly to the DC bus without any converter. Sections 2.3, 2.4, and 2.5 introduce different approaches for processing only a portion of the power from the photovoltaic source, with the latter presenting two distinct applications for PV systems. Finally, Section 2.6 summarizes the chapter’s key aspects and main conclusions.

2.1 Full Power Processing

The Full Power Processing (FPP) architecture involves routing all power from the source through converter elements—such as switches, inductors, and capacitors. Consequently, these components must be sized to handle the source’s nominal voltage and current, which subjects them to greater electrical stress and, therefore, higher losses when compared to elements operating at reduced voltage and current levels.

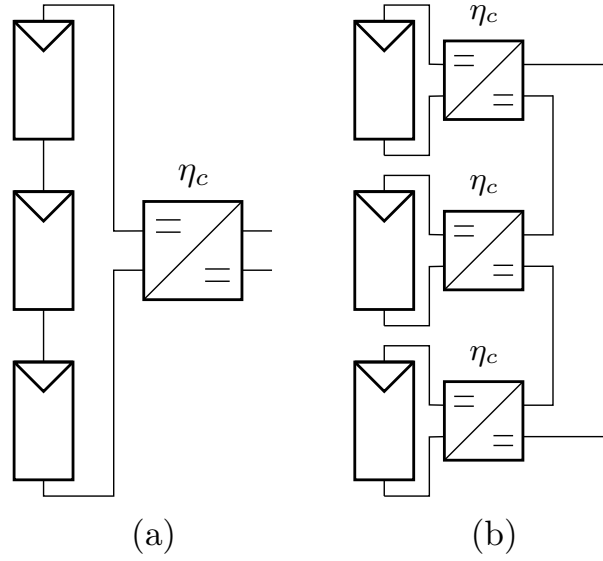
In this architecture, the connection between source and load to the converter follows a conventional arrangement: the source is connected in parallel with the input, and the load is connected in parallel with the output. Unlike Partial Power Processing (PPP), there is no interconnection between the source and the output terminal, nor between the load and the input terminal—a characteristic that will be analyzed in greater detail in Section 2.3.

When applied to PV systems, there are basically two types of FPP: centralized MPPT (CMPPT)—also known as field MPPT or standard MPPT—and distributed MPPT (DMPPT), illustrated in Figure 8 (Femia et al., 2017).

A CMPPT connects all PV modules to a single converter and, if operating conditions are uniform, it can ensure that the entire PV array operates at its maximum power point ($P_{mpp\ all}$). In contrast, a DMPPT connects each PV module—or smaller units such as sub-modules or cells—to an individual converter, allowing each to operate at its own P_{mpp} , even under differing conditions between the modules.

Considering “overall performance” as the ratio of power delivered to the DC bus

Figure 8 – Example of (a) centralized MPPT and (b) distributed MPPT.



Source: Author

to the maximum available power from the PV array, the overall performance of an FPP MPPT (ρ_{fpp})—for both CMPPT and DMPPT—is equal to the converter efficiency (η_c), since all PV modules are connected to the converter(s). That is to say, the performance of the architecture is entirely dependent on the efficiency of the converter.

$$\rho_{fpp} = \frac{P_{bus}}{P_{mpp\ all}} = \frac{\eta_c \cdot P_{mpp\ 1} + \eta_c \cdot P_{mpp\ 2} + \dots + \eta_c \cdot P_{mpp\ N}}{P_{mpp\ 1} + P_{mpp\ 2} + \dots + P_{mpp\ N}} = \frac{\eta_c \cdot P_{mpp\ all}}{P_{mpp\ all}} = \eta_c \quad (2.1)$$

Any type of converter can be used in this architecture, with the choice of topology depending on the load and the system's objectives. For economic reasons, CMPPT is the most widely adopted FPP configuration in PV systems, with the boost converter being the most common topology, commonly used to raise the PV array voltage level for compatibility with the input DC bus in grid-tied inverters.

In this case, employing a step-up converter implies that only maximum power points with voltages below the bus voltage (V_{bus}) can be tracked, as the converter's input voltage must remain lower than its output—where the DC bus is connected. Consequently, to determine the lowest feasible bus voltage, the maximum expected MPP voltage ($V_{mpp\ high}$) should be multiplied by the number of PV components connected in series (N).

$$V_{bus} = N \cdot V_{mpp\ high} \quad (2.2)$$

Similarly, if a step-down converter is used, the maximum DC bus voltage must be calculated by multiplying the minimum expected MPP voltage ($V_{mpp\ low}$) by the number of PV components connected in series.

$$V_{bus} = N \cdot V_{mpp\ low} \quad (2.3)$$

Consequently, if a step-up and step-down converter is employed, such as a buck–boost type, the bus voltage is not initially important.

2.2 No-Power Processing

The No-Power Processing (NoPP) architecture contrasts with FPP by eliminating converters altogether, allowing the PV array to connect directly to the DC bus. This architecture, when applied to a fixed DC bus, does not qualify as an MPPT method, as the bus voltage enforces a constant operating point on the PV components—preventing voltage variation and the active track of maximum power. The operating power will depend solely on the weather conditions, which determine the irradiance and temperature experienced by the PV cells.

Therefore, the overall performance of a NoPP system (ρ_{nopp}) is equal to the ratio of the operating PV power (P_{pv}) to the maximum available PV power (P_{mpp}). In a string with N PV components, operating under identical conditions, each component operates with the same performance as the system.

$$\rho_{nopp} = \frac{P_{bus}}{P_{mpp \text{ all}}} = \frac{N \cdot P_{pv}}{N \cdot P_{mpp}} = \frac{P_{pv}}{P_{mpp}} \quad (2.4)$$

Since there are no conversion losses, the system's performance is affected only by the lack of control—once the PV array is not guaranteed to operate at its maximum power point. However, the system can reach 100% performance if the maximum power point coincides with the operating point imposed by the bus voltage. That is to say, the performance of the architecture is entirely dependent on the weather conditions of the converter.

Designing a system based on this architecture requires climate history data for the target installation site. By combining this information with the characteristics of the PV cells, it becomes possible to estimate the expected maximum power point (MPP) voltages and, in turn, define the appropriate DC bus voltage.

An appropriate DC bus voltage for this architecture is determined by multiplying the mean maximum power point voltage ($V_{mpp \text{ mean}}$)—calculated from the expected voltage range—by the number of PV components connected in series (N). Using the mean value minimizes the discrepancy between the PV module operating voltage and its minimum and maximum expected values.

$$V_{bus} = N \cdot V_{mpp \text{ mean}} \quad (2.5)$$

2.3 Partial Power Processing

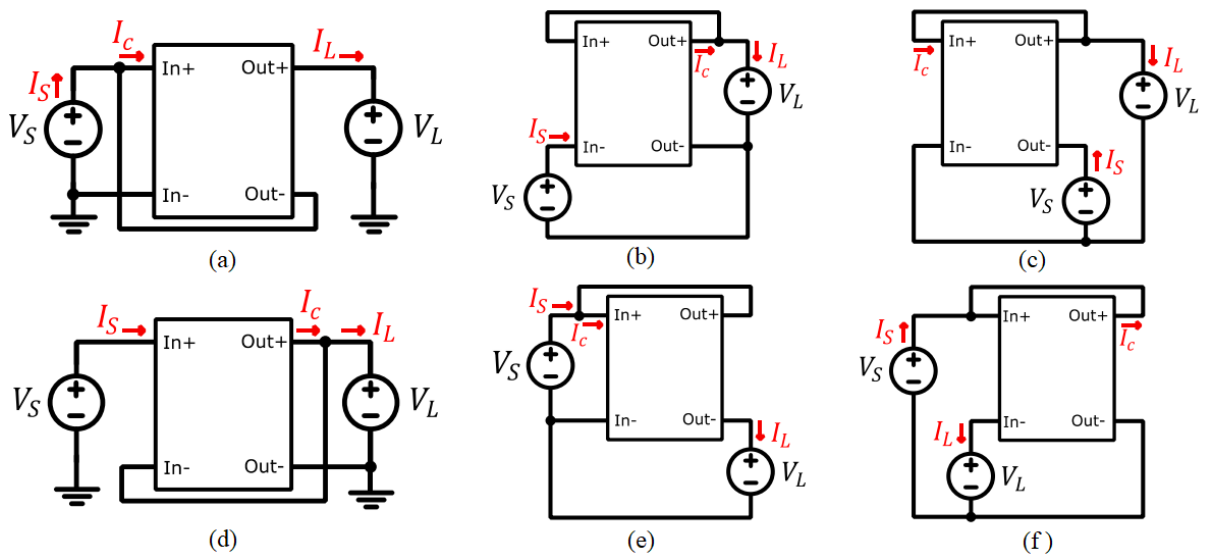
In general, Partial Power Processing (PPP) refers to any architecture that processes only a portion of the total power (Anzola et al., 2020), including approaches like Differential and Fractional Power Processing, which are discussed in detail in the following sections. More specifically, PPP denotes an architecture that employ converters as series regulators to control the voltage of a source—commonly known as Partial Power Converters (PPC) or Series-Connected Partial Power Converters (S-PPC) (Zientarski et al., 2017).

When connected in series, the source or load voltage—depending on the configuration—adds to the converter’s input or output voltage. As a result, any variation in the converter’s static gain directly influences the source or load voltage or current.

There are various types of PPC, as illustrated in Figure 9. These are classified based on their configuration—whether the input and output terminals of the converter are connected in series or parallel with the source and the load. The main categories include Input-Series Output-Parallel (ISOP) and Input-Parallel Output-Series (IPOS).

These unconventional connections allow a portion of the source’s active power to reach the load without passing through the converter. For example, in the circuit illustrated in Figure 9a, the load voltage (V_L) is the sum of the power converter’s output voltage (V_C) and the source voltage (V_S). This implies that part of the active power delivered to the load (P_L) is processed by the converter (P_C), while the remainder ($P_{S\ dir}$) comes directly

Figure 9 – PPC architectures types: (a) IPOS step-up. (b) ISOP-I step-up. (c) ISOP-II step-up. (d) ISOP step-down. (e) IPOS-I step-down. (f) IPOS-II step-down.



S: Source, L: Load, and PC: Power Converter

Source: Modified from Anzola et al. (2020)

from the source—assuming losses are negligible—as described by (2.6), (2.7), and (2.8).

$$V_L = V_S + V_C \quad (2.6)$$

$$I_S = I_L + I_C \quad (2.7)$$

$$P_L = V_L \cdot I_L = (V_S + V_C) \cdot I_L = P_{S \text{ dir}} + P_C \quad (2.8)$$

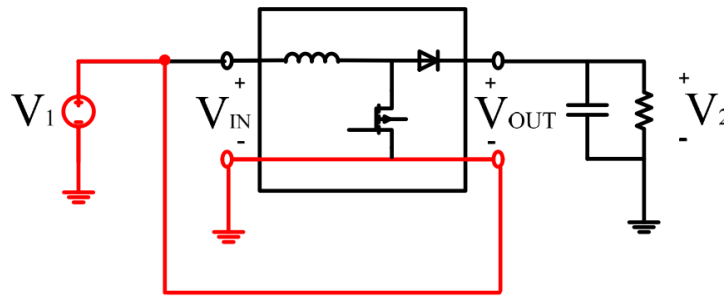
Thus, the amount of active power processed is determined by the voltage difference between the load and the source. In PV applications, this implies that the extent of the MPPT voltage operating range dictates how much power requires conversion (Zientarski et al., 2017).

One of the drawbacks of S-PPC architecture include the need for isolated converters in most cases. This isolation is required to prevent short circuits at the input source—as illustrated in Figure 10—and to ensure that the new configuration does not behave as a Full Power Processing (FPP) circuit (Zhao; Yeates; Han, 2013).

Even in applications where non-isolated converters can be used, a series connection alone is not a sufficient condition to reduce the amount of processed active power when compared to FPCs (Santos; Zientarski; Martins, 2021).

Although this architecture is designed to reduce active power processing, achieving the full benefits of downsized converter components and improved efficiency also depends on minimizing the handling of non-active power (Zientarski et al., 2015). In this context, the use of isolated converters becomes essential, as only certain topologies can effectively reduce both active and non-active power (Zientarski et al., 2017).

Figure 10 – Example of a short circuit in a non-isolated PPC.



Source: Zhao, Yeates and Han (2013)

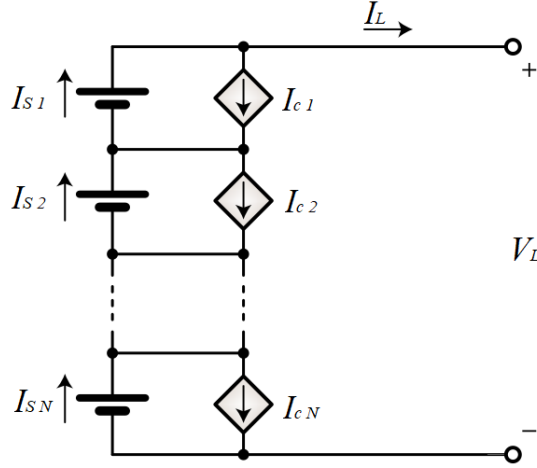
2.4 Differential Power Processing

The Differential Power Processing (DPP) architecture employs parallel regulators to control the current of individual power sources—commonly known as Differential Power Converters (DPC) or Parallel-Connected Partial Power Converters (P-PPC) (Zientarski et al., 2017).

When connected in parallel, the converters operate by subtracting current (I_c) from the source (I_S) before it reaches the load (I_L), as illustrated in Figure 11 and described by (2.9). As a result, any variation in the converter's static gain directly influences the source or load current.

$$I_L = I_{S1} - I_{c1} = I_{S2} - I_{c2} = \dots = I_{SN} - I_{cN} \quad (2.9)$$

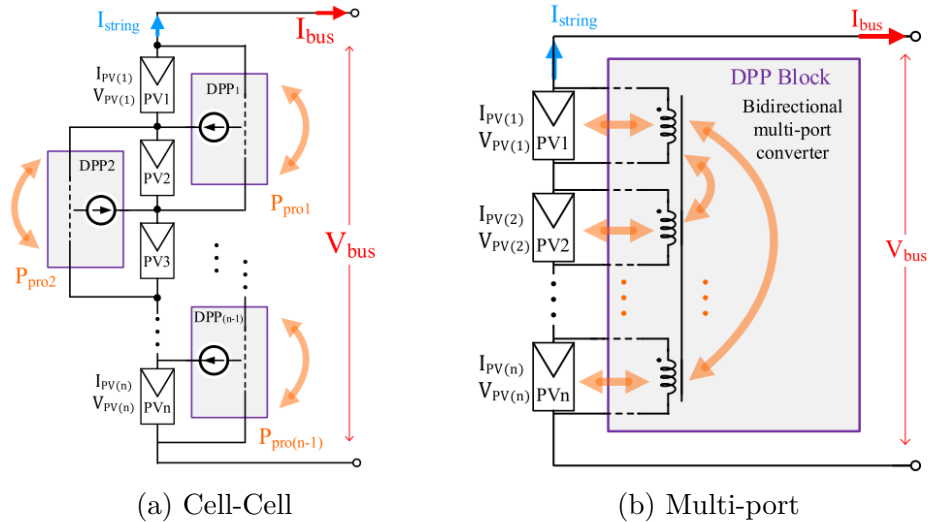
Figure 11 – Parallel regulators serving to balance the currents drawn from voltage sources.



Source: Modified from Zientarski et al. (2017)

Traditionally, DPP architectures are categorized into two types, as illustrated in Figure 12: cell-cell and multi-port configurations (Li; Cobos, 2021). The cell-cell type is implemented between adjacent power sources and enables localized power exchange. In contrast, the multi-port type connects all sources to a common load bus or virtual bus, facilitating global power exchange among all sources.

Figure 12 – Traditional DPP architecture types.



Source: Li and Cobos (2021)

Because this architecture is designed to balance power among sources, it is only applicable in systems with multiple inputs—unlike PPC, which can operate with a single source. This requirement also makes the architecture less economically attractive, as it necessitates multiple converters or converter designs featuring multiple input ports.

The primary drawback of applying DPP in PV systems lies in the system’s inherently high operating current variability, which is directly influenced by irradiance conditions. Under partial shading, significant discrepancies can arise between the MPP current of a PV cell and the output load current. Because the power processed by DPCs is proportional to the current difference between the source (I_S) and the load (I_L), the nominal rating of the converters cannot be significantly lower than the power of the associated PV sources (Zientarski et al., 2017).

2.5 Fractional Power Processing

The Fractional Power Processing (FRPP) architecture employs converters as series regulators to control the voltage of a source, similar to PPP approach. However, the key difference lies in the use of an auxiliary power source to supply the converter.

When a separate power source is used to supply the converter, the terminal connections remain conventional, with no direct link between the input and output. As a result, the power flow is equivalent to that in an FPC, but the converter is dimensioned solely for the auxiliary source—typically smaller than the main source and consistently less than the combined power of both. This configuration permits the use of simple, non-isolated topologies.

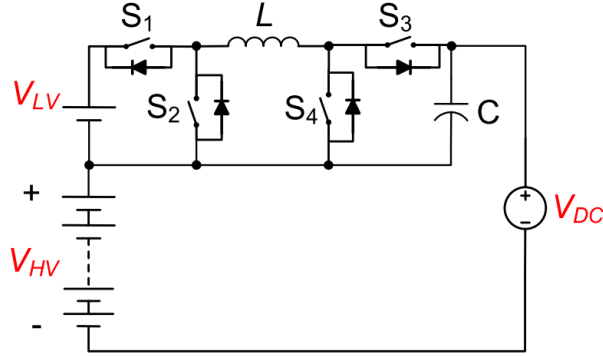
That is the reason why this study intentionally avoids the term “Fractional Power Converter”, as there is no distinct characteristic in either the converter itself or its terminal configuration. The topology simply reflects a FPC whose output is connected in series with other sources and the load.

Since an auxiliary power source is required, this architecture is unsuitable for single-source systems—unlike Partial Power Processing (PPP), which can function with a single input. It is better suited to modular configurations, such as those found in battery-based setups or PV systems. Figure 13 illustrates an example of a FRPP architecture applied to an energy storage system (Xue; Yu; Huang, 2020).

Given that the literature review, in Section 1.2, revealed a lack of sufficient studies addressing the application of FRPP in PV systems, this work now proposes possible configurations for implementing MPPT within FRPP architectures.

The generic model of the proposed architecture consists of a PV source representing a PV string with n PV components (modules or cells), henceforth called the main string,

Figure 13 – Example of a FRPP architecture applied to an ESS.



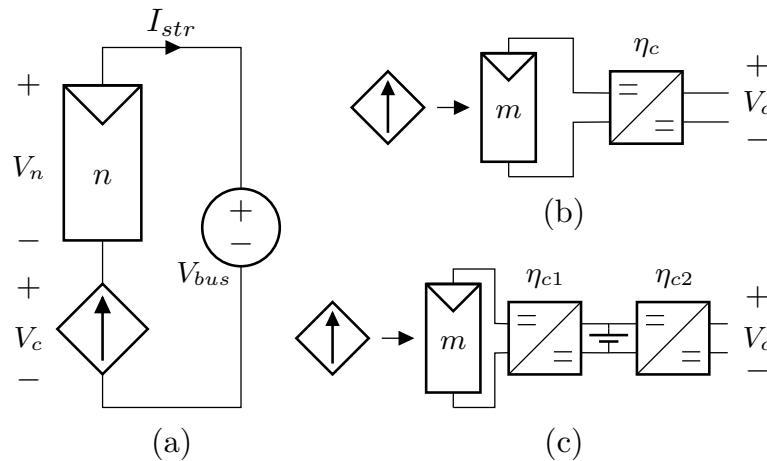
Source: Xue, Yu and Huang (2020)

connected in series to a controlled current source, which represents a DC converter powered by an auxiliary source. This is then connected to a voltage source, representing a fixed DC bus. The current source is actively controlled to ensure that the string current matches the MPP current value of the main string. The described circuit is illustrated in Figure 14a, which also includes the symbols needed to describe the system.

Since PV components can serve as both the main and auxiliary source, two different types of this application have been categorized: coupled and decoupled FRPP. The coupled FRPP (CFRPP) utilizes an auxiliary PV string composed of m PV components, directly connected to the converter, as shown in Figure 14b and explored in Section 4. In contrast, the decoupled FRPP (DFRPP) enables the two PV sets to operate independently by interfacing an energy storage system (ESS) with the converter while employing m PV components for recharging, as pictured in Figure 14c and discussed in Section 5. In both configurations, a portion of the PV system serves as the auxiliary source.

Figure 14 – Fractional Power Processing Architecture applied on PV systems:

(a) Generic circuit. (b) Coupled type source. (c) Decoupled type source.



Source: Author

To reinforce the parallel between FRPP and FPP, it is worth noting the resemblance between CFRPP and the DMPPT system. However, while DMPPT systems configure the converter to track the maximum input power from individual sources, CFRPP focuses on the maximum power point of the main string—located at the system output.

When a PV source is used as auxiliary source without an accompanying ESS, the auxiliary power output is limited by the power curve of the auxiliary PV string. This constraint introduces a coupling between the main and auxiliary PV sets, preventing the converter's output power (P_c) from exceeding the maximum power point of the auxiliary string (P_{m_mpp}). By incorporating an ESS, the two PV strings become decoupled, enabling independent operation. In this configuration, the relationship between P_c and P_{m_mpp} governs the battery's charge and discharge durations. These dynamics are summarized in Table 1.

Table 1 – Operating states for each FRPP type, based on the auxiliary source power level.

	Coupled	Decoupled
$P_c = P_{m_mpp}$	Ideal state	Floating state
$P_c < P_{m_mpp}$	Possible state	Charging state
$P_c > P_{m_mpp}$	Impossible state	Discharging state

Based on the number of photovoltaic (PV) components in series within the main and auxiliary strings—denoted n and m , respectively—two key ratios are defined. The first, r , described in Equation (2.10), represents the proportion of PV components in the main string relative to the auxiliary string. The second, f , presented in Equation (2.11), quantifies the ratio between the maximum power of the auxiliary string and the total system power, thereby indicating the fraction of power processed by the converters. These ratios will be used throughout the following chapters to characterize the FRPP architecture.

$$r = \frac{n}{m} \quad (2.10)$$

$$f = \frac{m.P_{mpp}}{(n+m).P_{mpp}} = \frac{1}{r+1} \quad (2.11)$$

The overall performance of the proposed FRPP system (ρ_{frpp}) is defined by the ratio between the total extracted power—comprising the maximum power from the main string ($n.P_{mpp}$) and the converter output power (P_c)—and the maximum available PV power ($(n+m).P_{mpp}$). The converter's output power P_c is a function of the auxiliary string's operating power ($m.P_{pv}$) and the converter efficiency (η_c), however, its precise formulation varies depending on the specific type of FRPP architecture.

$$\rho_{frpp} = \frac{n.P_{mpp} + P_c}{(n+m).P_{mpp}} \quad (2.12)$$

2.6 Chapter Conclusion

This chapter introduced and examined various power processing architectures.

FPP architecture offers the advantage of guaranteeing maximum power output across any operating voltage range—assuming an appropriate load voltage level. However, this approach requires converters capable of handling the system’s full nominal power, with active and passive components designed to withstand the maximum expected current and voltage.

NoPP architecture offers the advantage of eliminating switching losses and parasitic elements, as it operates without converters. However, it does not perform MPPT and relies entirely on ambient climatic conditions to determine PV operating point.

By employing voltage regulators, PPP architecture is capable of handling only part of the active power generated by the source. Consequently, in PV applications, the extent of the MPPT voltage operating range determines the required level of power conversion. However, to fully realize benefits such as reduced converter sizing and improved efficiency, PPP requires specific isolated topologies.

By employing current regulators, DPP architecture can handle only the power difference between sources. As a result, in PV applications, the extent of the MPPT current operating range determines the required level of power conversion. However, since MPP current variation tends to be significantly greater than MPP voltage variation—and due to the need for multiple converters—the implementation of this architecture in PV systems is generally less appealing.

The application of FRPP architecture to photovoltaic systems represents an alternative method for partial power conversion. Like PPP, FRPP operates by regulating voltage. However, it employs converters with simple, non-isolated topologies and conventional connections, enabling a power flow equivalent to that of a full power converter. Two types of FRPP architectures have been introduced and will be discussed in detail in the following chapters.

3 Architecture Evaluation and Validation Methodology

The two proposed FRPP architectures, introduced in Section 2.5 detailed in Chapters 4 and 5, were computationally simulated to validate their respective mathematical models and evaluate performance. Section 3.1 defines the metrics used for validation, comparison and evaluation. Section 3.2 details the simulation procedures for all architectures. Section 3.3 presents the benchmark architectures selected for comparison, along with the results of their respective simulations. Section 3.4 provides the specific formulas used to evaluate the simulated scenarios, based on the presented metrics. Finally, Section 3.5 summarizes the key findings and conclusions drawn from this chapter.

3.1 Comparison Metrics

3.1.1 Validation

Chapters 4 and 5 introduce equations that describe the behavior of the proposed FRPP architectures. Accordingly, simulations can validate these equations by calculating the mean absolute error (MAE) between simulated and theoretically derived values for selected quantities of interest, using Equation (3.1).

$$MAE = \frac{\sum_{p=1}^{p_{tot}} |y_p - x_p|}{p_{tot}} \quad (3.1)$$

where y is the simulated value, x is the theoretical value, p is the index used to identifying each data point, p_{tot} is the total number of data points.

3.1.2 Evaluation

The overall performance of a PV system reflects both MPPT performance and conversion efficiency (Femia et al., 2017), and represents a key metric for evaluation, as it encapsulates the system's ability to deliver power.

In the first stage of conversion—DC-DC only—the overall performance of a PV system can be defined as the ratio of the power reaching the DC bus (P_{bus}) to the maximum available power from all the PV components ($P_{mpp \text{ all}}$).

$$\rho_{syst} = \frac{P_{bus}}{P_{mpp \text{ all}}} \quad (3.2)$$

To compare the overall performance in tests involving multiple operating points, two averaging methods were considered: a simple average, assuming each operating point is equally likely to occur during operation; and a weighted average, based on a normal distribution of the V_{mpp} values, where values closer to the mean occur more frequently, as described in Zientarski et al. (2017) and Zientarski et al. (2017).

Since the simple average assumes that all operating voltage points are equally likely to occur, the simple average performance is calculated by summing the operating power at each point and dividing by the sum of the maximum available power at each point, as shown in Equation (3.3).

$$\rho'_{syst} = \frac{\sum_{p=1}^{p_{tot}} P_{bus,p}}{\sum_{p=1}^{p_{tot}} P_{mpp\ all,p}} \quad (3.3)$$

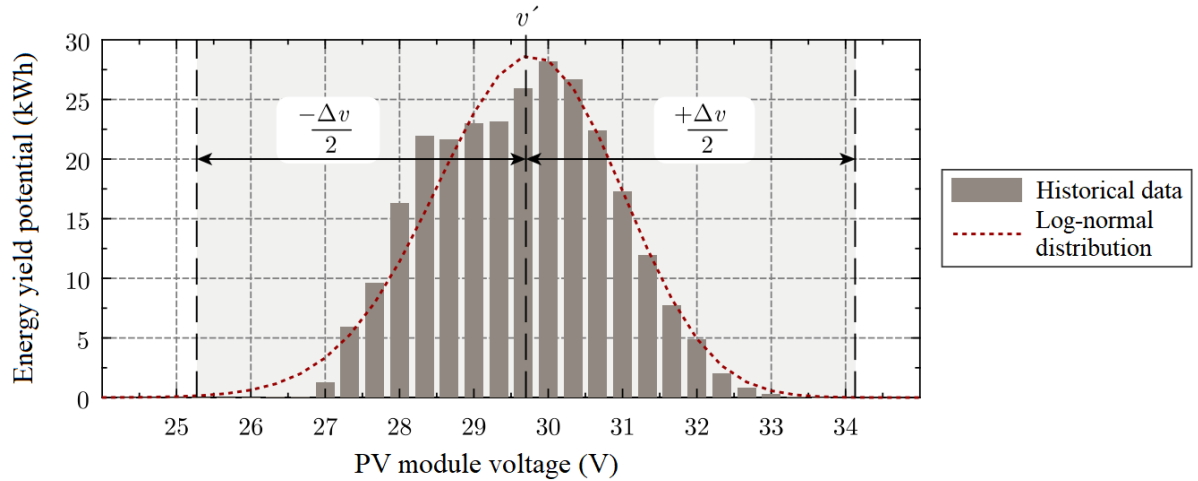
For a more realistic approach, it is assumed that PV modules operate within a maximum power voltage range (ΔV_{mpp}), and that energy production follows a normal distribution across this range—yielding more energy at voltage levels near the mean value, as illustrated in Figure 15. ΔV_{mpp} is given by Equation (3.4).

$$\Delta V_{mpp} = \frac{V_{mpp\ high} - V_{mpp\ low}}{V_{mpp\ mean}} \quad (3.4)$$

where $V_{mpp\ high}$, $V_{mpp\ low}$, and $V_{mpp\ mean}$ represent, respectively, the highest, lowest, and mean V_{mpp} values within the range.

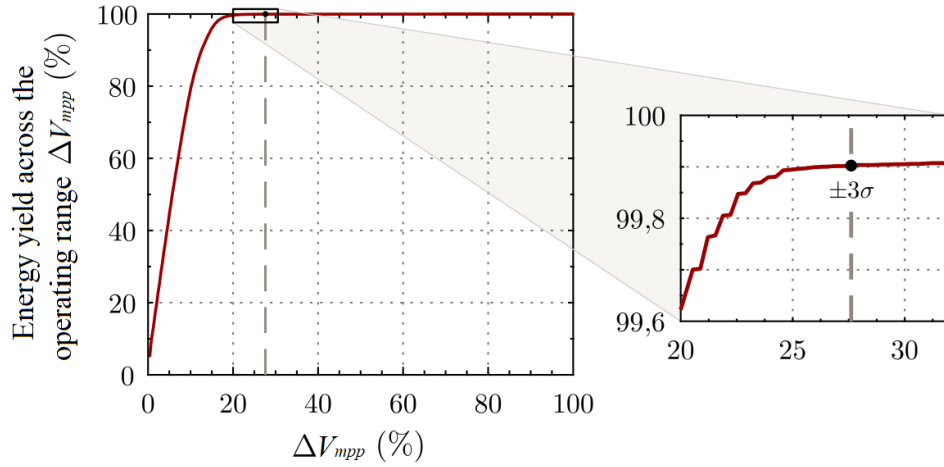
According to Zientarski et al. (2017), 99.9% of the generation potential is concentrated within a range of six standard deviations, which defines the value of ΔV_{mpp} , as illustrated in Figure 16. Therefore, PV systems should be designed to operate with a maximum power voltage variation of at least $\pm 3\sigma$.

Figure 15 – Energy yield curve over voltage range.



Source: Modified from Zientarski et al. (2017)

Figure 16 – Percentage of energy generated across the operating voltage range.



Source: Modified from [Zientarski et al. \(2017\)](#)

Using the three-sigma rule, the percentage of energy production within each 1σ band—illustrated in Figure 17—can be approximated, enabling the definition of weights k_σ for the weighted average.

$$k_{\sigma,1} = 0.022 \quad (3.5)$$

$$k_{\sigma,2} = 0.136 \quad (3.6)$$

$$k_{\sigma,3} = 0.341 \quad (3.7)$$

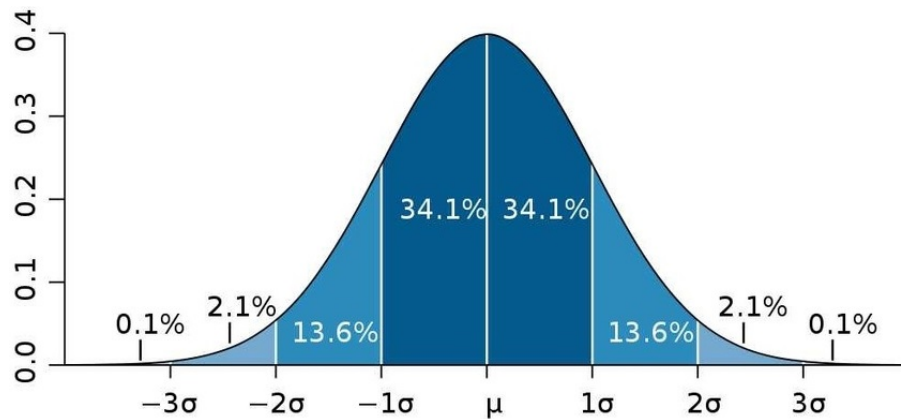
$$k_{\sigma,4} = 0.341 \quad (3.8)$$

$$k_{\sigma,5} = 0.136 \quad (3.9)$$

$$k_{\sigma,6} = 0.022 \quad (3.10)$$

With the weights k_σ defined, the remaining step is to group the simulated power values into P_σ values corresponding to each one-standard-deviation band, allowing them to be

Figure 17 – Three sigma rule.



Source: [Chandler \(2012\)](#)

multiplied by the appropriate weight, as defined by Equation (3.11).

$$\rho''_{syst} = \frac{\sum_1^6 k_{\sigma,i} \cdot P_{bus \sigma,i}}{\sum_1^6 k_{\sigma,i} \cdot P_{mpp \ str \ \sigma,i}} \quad (3.11)$$

3.2 Simulation Setup

The simulations were carried out using PSIM, utilizing both the Thermal and Renewable Modules. The Thermal Module accounts for MOSFET switching and conduction losses, while the Renewable Module enables the use of a physical PV cell model within the simulation.

The simulated PV array was composed of twelve modules—model CS6U-330P, Canadian Solar—detailed in Table 2. All architectures were simulated with the same total amount of modules. The simulation considers the number of cells in series, with each module consisting of 72 cells divided into three submodules, each marked by the use of a bypass diode for every group of 24 cells.

To allow for greater design flexibility in the FRPP application, the simulations considered the possibility of grouping submodules to form the main and auxiliary strings, with the understanding that electrical contact with the submodule can be accessed through the junction box of a commercial PV module.

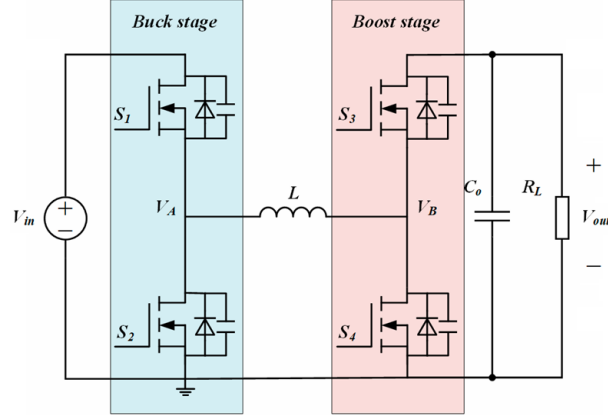
For architectures that require power processing, the same converter was used: a non-ideal four-switch buck–boost converter accounting for switching and conduction losses, considering 3°C/W as the thermal resistance for each MOSFET and an ambient temperature of 20°C. The software estimates switch losses by incorporating in various electrical parameters specified in the datasheet, including switch resistance, rise and fall times, transconductance, parasitic capacitances, and other relevant characteristics. The MOSFET parameters used in the simulation—along with their corresponding values—are shown in Figure 36, located in Appendix A.

Table 2 – Canadian Solar CS6U-330P PV module specification (STC)

Parameter	Value
Number of Cells	72 (in series)
Cell Nominal Maximum Power (P_{mpp})	4.583 W
Cell Open-Circuit Voltage (V_{oc})	0.633 V
Cell Short-Circuit Current (I_{sc})	9.45 A
Cell Maximum Power Point Voltage (V_{mpp})	0.517 V
Cell Maximum Power Point Current (I_{mpp})	8.88 A
P_{mpp} Temperature Coefficient	−0.40 %/°C
V_{oc} Temperature Coefficient	−0.31 %/°C
I_{sc} Temperature Coefficient	0.05 %/°C

The choice to use the same converter aimed to ensure a fair comparison of the architectures' performances, given that identical active and passive components and the same MPPT perturb and observe (P&O) algorithm were applied. The topology structure of the converter is illustrated in Figure 18. Additional information about the converter parameters used in the simulation can be found in Table 3, while the corresponding design methodology is presented in Appendix A.

Figure 18 – Topology structure of a four-switch buck–boost converter.



Source: Modified from Lin, Li and Zhang (2025)

In FPP simulation, the P&O algorithm calculates power using input voltage and current. In contrast, for FRPP, the algorithm of the converter that regulates the main string current uses bus voltage, converter output voltage, and converter output current for its power computation. Aside from these input differences, the algorithm operates identically in both architectures, employing the same duty cycle adjustment step of $\Delta D = 0.0025$, which was defined as sufficiently small to ensure that oscillations around the maximum power point do not interfere with the system's performance analysis.

The four-switch buck–boost converter was chosen because it is a step-down/step-up voltage topology, ensuring that the maximum PV power point is reached under any scenario. Additionally, it can operate in both buck and boost modes, resembling topologies commonly used in PV applications.

By switching all four switches, the converter operates in Buck–Boost mode; however,

Table 3 – Converter Parameters

Parameter	Value
MOSFET Model	IRFP460
Inductor	100 μH
Inductor ESR	30 $\text{m}\Omega$
Capacitor (In and Out)	100 μF
Capacitor ESR	1 $\text{m}\Omega$
Switching Frequency	20 kHz

it is also possible to switch only the Buck stage or the Boost stage to operate in Buck or Boost mode, respectively. For Buck mode, S_1 and S_2 are complementary, and their duty cycle defines the converter gain, while S_3 remains open and S_4 remains closed. Similarly, for Boost mode, S_3 and S_4 are complementary, and their duty cycle defines the converter gain, while S_1 remains closed and S_2 remains open.

To control the operating modes, instead of using a dual-carrier approach, a unified control variable D is implemented, ranging from 0 to 2 (Lin; Li; Zhang, 2025). This variable defines the duty cycles D_{buck} , for switch S_1 and, complementarily, S_2 ; and D_{boost} , for S_3 and, complementarily, S_4 . Both duty cycles are limited to values between 0 and 1 and are compared with a single triangular carrier oscillating from 0 to 1.

$$D_{buck} = D \quad (3.12)$$

$$D_{boost} = D - 1 \quad (3.13)$$

Therefore, to analyze the converter's operating mode, one can simply check the value of D shown in the simulation results tables: for $D < 1$, the converter operates in Buck mode; for $D > 1$, in Boost mode.

The benchmark architectures were simulated in two different scenarios: with a wide operating range of $\Delta V_{mpp} = 28\%$, which was the highest value found among the Brazilian cities analyzed in Zientarski et al. (2017) and Zientarski et al. (2017); and another with a narrow operating range of $\Delta V_{mpp} = 2\%$, defined as sufficiently small to contrast with the previous scenario and enable comparison of the architectures' responses.

For the first scenario ($\Delta V_{mpp} = 28\%$), the temperature was varied from 5°C to 75°C in steps of 7°C , resulting in eleven V_{mpp} values; and for the second one ($\Delta V_{mpp} = 2\%$), it was varied from 52°C to 57°C in steps of 1°C , resulting in six V_{mpp} values. In both scenarios, the irradiance was kept at 1000 W/m^2 .

The irradiance and temperature profiles applied in the simulation are not representative of real-world conditions, as a temperature variation of 70°C —from 5°C to 75°C —combined with a high and constant irradiance of 1000 W/m^2 is unlikely to occur. These profiles are used solely to emulate the voltage operating range as a proof of concept, demonstrating that the architectures can operate at specific V_{mpp} values. They are not suitable for evaluating annual power generation, as this is not the scope of this study. Even so, they are sufficient to demonstrate the operation of the proposed architectures and to compare them with different systems, since the scenarios are the same.

To ensure a fair comparison, a distinct bus voltage (V_{bus}) was assigned to each architecture based on its operational characteristics, with the aim of selecting an optimal value for the performance of each system.

The simulation, performed with a time-step of 50 ns, verifies the system's values of interest for each operating point, defined by the values of V_{mpp} , starting from the moment the MPPT stabilizes the PV modules at their maximum power point. Then, the overall performance values, ρ_{sys} , are calculated for each operating point, along with the simple and weighted average performance values, according to (3.2), (3.3), and (3.11), respectively.

Additionally, for the FRPP architectures, other variables of interest will be calculated and compared with expected values to validate the theoretical analysis.

3.3 Benchmark Architectures

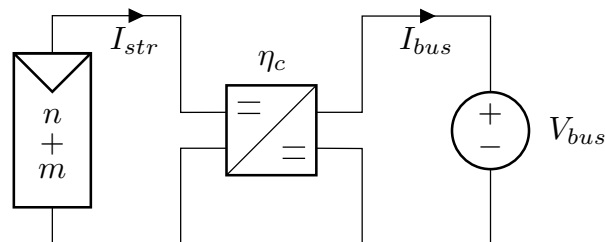
To evaluate FRPP, its overall performance will be compared to two extremes in terms of power processed: a system with full power processing (FPP) and another with no power processing (NoPP).

For the FPP system, a centralized MPPT (CMPPT) approach was chosen, as it is the dominant configuration in commercial setups, in contrast to distributed MPPT (DMPPT). For the NoPP system, the PV modules were connected directly to the bus.

For the centralized MPPT system, the simulated circuit is shown in Figure 19, with twelve modules ($n + m = 864$ cells) connected to a converter that tracks the string's maximum power point, and with its output connected to a constant-voltage DC bus, $V_{bus} = 482$ V for the wide-range scenario and $V_{bus} = 401$ V for the narrow-range scenario. The DC bus voltage levels were defined based on the highest V_{mpp} values to ensure that the converter operates in boost mode, which is the most common topology used in centralized MPPT systems, as explained in Section 2.1.

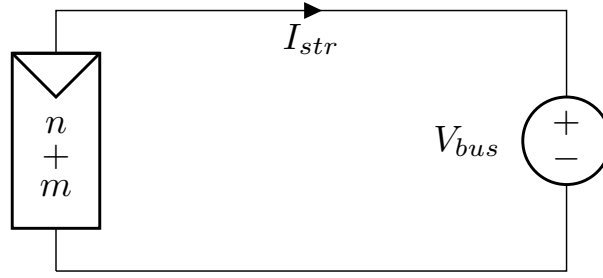
For the direct bus-connected architecture, the simulated circuit is shown in Figure 20, with twelve modules ($n + m = 864$ cells) connected directly to a constant-voltage DC bus, $V_{bus} = 421$ V for the wide-range scenario and $V_{bus} = 396$ V for the narrow-range scenario. The DC bus voltage levels were defined based on the mean V_{mpp} value in order to reduce the difference between the PV module voltage and the extreme V_{mpp} values, $V_{mpp\ low}$ and

Figure 19 – Full power processing (FPP) circuit simulated in PSIM.



Source: Author

Figure 20 – No-power processing (NoPP) circuit simulated in PSIM.



Source: Author

$V_{mpp \text{ high}}$, since this architecture does not operate as an MPPT, as explained in Section 2.2.

The simulation setup, defined in Section 3.2, is identical for all architectures. The simulation results for the benchmark architectures are presented in Tables 4, 6, 5, and 7, with voltage in volts (V) and power in watts (W). The value p is an index used to identify the operating point. The values V_{pv} and V_{mpp} correspond, respectively, to the operating voltage and the maximum power point voltage of the PV module, considering 72 grouped cells. The values $P_{pv \text{ all}}$ and $P_{mpp \text{ all}}$ correspond, respectively, to the operating power and maximum power of the string, considering the 12 grouped PV modules.

Table 4 – Operation and Performance of the Centralized MPPT System (FPP) in the Wide-Range Scenario

p	V_{pv}	D	$P_{mpp \text{ all}}$	$P_{pv \text{ all}}$	P_{loss}	P_{bus}	η_c	ρ_{syst}
1	30.2	1.26	3135.6	3135.3	131.5	3003.8	95.8%	95.8%
2	31.1	1.23	3250.4	3250.1	121.8	3128.3	96.3%	96.2%
3	32.1	1.21	3365.5	3365.3	110.4	3254.9	96.7%	96.7%
4	33.1	1.18	3480.9	3480.8	99.0	3381.8	97.2%	97.2%
5	34.1	1.16	3596.7	3596.5	87.4	3509.1	97.6%	97.6%
6	35.1	1.13	3712.7	3712.5	76.1	3636.4	98.0%	97.9%
7	36.0	1.11	3828.9	3828.8	66.5	3762.3	98.3%	98.3%
8	37.0	1.08	3945.5	3945.3	55.8	3889.5	98.6%	98.6%
9	38.1	1.06	4062.0	4062.0	51.8	4010.2	98.7%	98.7%
10	39.1	1.04	4178.8	4178.7	49.0	4129.7	98.8%	98.8%
11	40.1	1.01	4295.7	4295.6	47.6	4248.0	98.9%	98.9%

Table 5 – Operation and Performance of the Centralized MPPT System (FPP) in the Narrow-Range Scenario

p	V_{pv}	D	$P_{mpp \text{ all}}$	$P_{pv \text{ all}}$	P_{loss}	P_{bus}	η_c	ρ_{syst}
1	32.7	1.03	3431.4	3431.4	42.2	3389.2	98.8%	98.8%
2	32.9	1.02	3448.0	3447.9	41.9	3406.0	98.8%	98.8%
3	33.0	1.02	3464.4	3464.3	42.0	3422.3	98.8%	98.8%
4	33.1	1.02	3481.0	3480.9	41.7	3439.2	98.8%	98.8%
5	33.3	1.01	3497.5	3497.5	41.6	3455.9	98.8%	98.8%
6	33.4	1.01	3514.0	3514.0	41.6	3472.4	98.8%	98.8%

Table 6 – Operation and Performance of the Direct Bus-Connected System (NoPP) in the Wide-Range Scenario

p	V_{mpp}	V_{pv}	$P_{mpp\ all}$	$P_{pv\ all}$	P_{bus}	ρ_{syst}
1	30.2	35.1	3135.6	2414.4	2414.4	77.0%
2	31.1	35.1	3250.4	2806.1	2806.1	86.3%
3	32.1	35.1	3365.5	3127.9	3127.9	92.9%
4	33.1	35.1	3480.9	3381.7	3381.7	97.2%
5	34.1	35.1	3596.7	3573.7	3573.7	99.4%
6	35.1	35.1	3712.7	3712.7	3712.7	100.0%
7	36.0	35.1	3828.9	3809.1	3809.1	99.5%
8	37.0	35.1	3945.5	3873.1	3873.1	98.2%
9	38.1	35.1	4062.0	3913.7	3913.7	96.3%
10	39.1	35.1	4178.8	3938.7	3938.7	94.3%
11	40.1	35.1	4295.7	3953.1	3953.1	92.0%

Table 7 – Operation and Performance of the Direct Bus-Connected System (NoPP) in the Narrow-Range Scenario

p	V_{mpp}	V_{pv}	$P_{mpp\ all}$	$P_{pv\ all}$	P_{bus}	ρ_{syst}
1	32.7	33.0	3431.4	3429.6	3429.60	99.9%
2	32.9	33.0	3448.0	3447.5	3447.50	100.0%
3	33.0	33.0	3464.4	3464.4	3464.40	100.0%
4	33.1	33.0	3480.7	3480.7	3480.70	100.0%
5	33.3	33.0	3497.5	3496.1	3496.10	100.0%
6	33.4	33.0	3514.0	3510.7	3510.70	99.9%

3.4 Benchmark Evaluation

To determine the simple average overall performance for each architecture, Equation (3.3) was applied by summing eleven values for the wide-range scenario and six for the narrow-range scenario.

In the wide-range scenario, FPP achieved a simple average overall performance of 97.8%, while NoPP reached 94.3%. In the narrow-range scenario, FPP attained 98.8%, and NoPP reached 100.0%.

To determine the weighted average overall performance for each architecture, the six P_σ values must be defined in order to apply Equation (3.11).

For the wide-range scenario, with eleven operating points— $\Delta V_{mpp} = 28\%$ —certain power values are averaged and treated as P_σ value, based on the following equations.

$$P_{\sigma,1} = P_1 \quad (3.14)$$

$$P_{\sigma,2} = \frac{P_2 + P_3}{2} \quad (3.15)$$

$$P_{\sigma,3} = \frac{P_4 + P_5 + P_6}{3} \quad (3.16)$$

$$P_{\sigma,4} = \frac{P_6 + P_7 + P_8}{3} \quad (3.17)$$

$$P_{\sigma,5} = \frac{P_9 + P_{10}}{2} \quad (3.18)$$

$$P_{\sigma,6} = P_{11} \quad (3.19)$$

For the narrow-range scenario, with six operating points— $\Delta V_{mpp} = 2\%$ and $\sigma = 0.33\%$ —the power values at each operating point are treated as P_σ value, as shown by the following equations.

$$P_{\sigma,1} = P_1 \quad (3.20)$$

$$P_{\sigma,2} = P_2 \quad (3.21)$$

$$P_{\sigma,3} = P_3 \quad (3.22)$$

$$P_{\sigma,4} = P_4 \quad (3.23)$$

$$P_{\sigma,5} = P_5 \quad (3.24)$$

$$P_{\sigma,6} = P_6 \quad (3.25)$$

With P_σ defined for each scenario, Equation (3.11) can now be applied. In the wide-range scenario, FPP achieved a weighted average overall performance of 97.9%, while NoPP reached 96.7%. In the narrow-range scenario, FPP attained 98.8%, and NoPP reached 100.0%.

This process will also be used to calculate the weighted average overall performance for the proposed FRPP architectures.

3.5 Chapter Conclusion

This chapter presented the evaluation criteria used to compare the architectures, the simulation setup applied to all configurations, and the details and results of the benchmark architecture simulations.

In the wide-range scenario, the NoPP architecture outperformed FPP only at three operating points ($p = 5$, $p = 6$, $p = 7$), where V_{mpp} was close to V_{pv} . When the simple and weighted averages are considered, the FPP architecture exhibits superior performance compared to NoPP.

In the narrow-range scenario, NoPP outperformed FPP on average and surpassing it at all operating points, as the operating range was narrowed to include only the region where NoPP exceeds FPP. In this scenario, the power loss from not reaching maximum power is lower than the converter losses incurred when attempting to bring the system to its maximum power point. The narrower the operating band, the better NoPP's average performance.

4 Coupled Fractional Power Processing

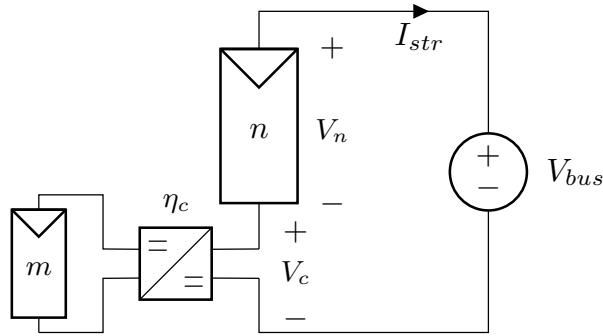
This chapter presents a novel investigation into how an FRPP architecture can be used as an MPPT for a PV system while exclusively using PV modules as auxiliary source (coupled FRPP). Section 4.1 introduces the mathematical model that describes the operational principles of the proposed architecture. Section 4.2 details the simulation procedure, presents the corresponding results, validates the developed model, and assesses the performance of the architecture. Finally, Section 4.3 summarizes the key findings and conclusions drawn from this chapter.

4.1 Theoretical Analysis

For the following analyses, both the main and auxiliary strings are assumed to consist of panels of the same model, operating under identical temperature and irradiance conditions, ensuring a consistent maximum power point voltage and current (V_{mpp} and I_{mpp}) value across all panels.

The coupled FRPP circuit is illustrated in Figure 21, which also includes some of the symbols needed to describe the system.

Figure 21 – Coupled fractional power processing (CFRPP) circuit.



Source: Author

4.1.1 MPPT range with a Coupled Auxiliary Source

Considering that the purpose of the system is to ensure that the main string PV components reach their maximum power point (P_{mpp}), the main string current (I_{str}), voltage (V_n), and operating power (P_n) are defined by the following equations.

$$I_{str} = I_{mpp} \quad (4.1)$$

$$V_n = V_{bus} - V_c = n \cdot V_{mpp} \quad (4.2)$$

$$P_n = V_n \cdot I_{str} = n \cdot P_{mpp} \quad (4.3)$$

To achieve (4.1) and (4.2) for varying values of V_{mpp} , the converter's output voltage (V_c) must adapt as the bus voltage (V_{bus}) remains fixed. As a result, the permissible range of V_{mpp} is directly linked to the operating range of V_c , which is influenced by the auxiliary source power (P_c), which, in turn, is limited by the power curve of the auxiliary string (P_m). This coupling relationship gives the source type and the architecture their defining names: Coupled Auxiliary Source and Coupled Fractional Power Processing Architecture.

$$P_c = V_c \cdot I_{str} = \eta_c \cdot P_m \quad (4.4)$$

η_c represents the efficiency of the converter.

To represent the variation of P_m , which ranges from 0 to the auxiliary string maximum available power ($m \cdot P_{mpp}$), the auxiliary-source factor, μ , is defined, ranging from 0 to 1.

$$\mu = \frac{P_m}{m \cdot P_{mpp}} \quad (4.5)$$

By substituting (4.1) into (4.4), and subsequently (4.4) into (4.5), a correlation can be established between the auxiliary string power and the operating range of V_c . Since the output current of the converter is regulated to I_{mpp} , the maximum value of V_c corresponds to the highest-power voltage at the converter's output.

$$V_c = \mu \cdot \eta_c \cdot m \cdot V_{mpp} \quad (4.6)$$

Based on (4.2) and (4.6), the range of values that V_{mpp} can assume may also be explicitly determined.

$$V_{mpp} = \frac{V_{bus}}{n + \mu \cdot \eta_c \cdot m} \quad (4.7)$$

Thus, the coupled FRPP architecture can harvest maximum power from the main string when the value of V_{mpp} lies between $V_{bus}/(n + \eta_c \cdot m)$ and V_{bus}/n . However, this results in underutilizing the auxiliary string. As μ decreases, the power extracted from the auxiliary string diminishes, while the voltage range of the main string expands.

The operating range of the main string (ΔV_{mpp}) is defined as the difference between the highest and lowest V_{mpp} values, divided by the mean V_{mpp} value. The lowest value ($V_{mpp \text{ low}}$) happens when $\mu = 1$ and the highest value ($V_{mpp \text{ high}}$) depends on μ .

$$V_{mpp \text{ low}} = \frac{V_{bus}}{n + \eta_c \cdot m} \quad (4.8)$$

$$V_{mpp \text{ high}} = \frac{V_{bus}}{n + \mu \cdot \eta_c \cdot m} \quad (4.9)$$

$$\Delta V_{mpp} = \frac{V_{mpp \text{ high}} - V_{mpp \text{ low}}}{V_{mpp \text{ low}} + (V_{mpp \text{ high}} - V_{mpp \text{ low}})/2} \quad (4.10)$$

The μ factor is constrained between 0 and 1, which allows the voltage range ΔV_{mpp} to be defined starting from either $V_{mpp \text{ low}}$ or $V_{mpp \text{ high}}$. In this analysis, the ΔV_{mpp} is defined starting from $V_{mpp \text{ low}}$ to ensure that the ideal value $\mu = 1$ —which corresponds to maximum power generation in the auxiliary string—falls within the valid operating domain.

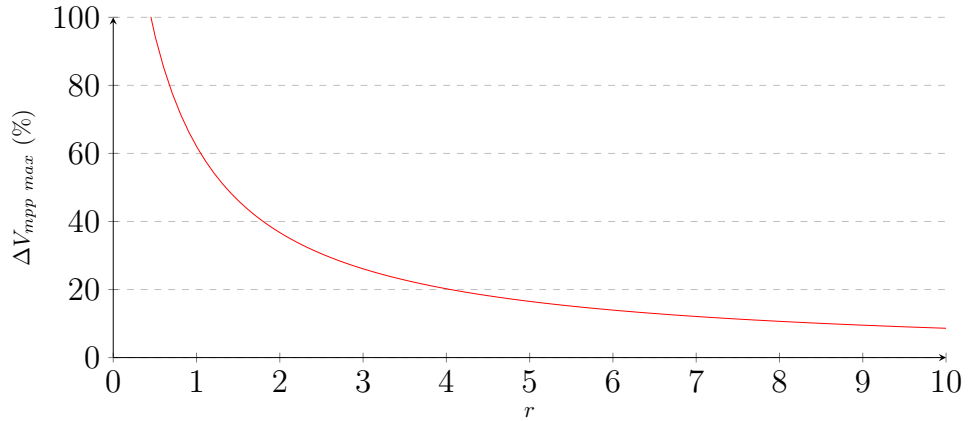
By applying (4.8) and (4.9) to (4.10), and applying r —that represent the ratio of the number of PV components in the main string to those in the auxiliary string ($r = n/m$), as described in (2.10)— ΔV_{mpp} is defined as a function of r and μ .

$$\Delta V_{mpp} = \frac{2 \cdot \eta_c \cdot (1 - \mu)}{2 \cdot r + \eta_c \cdot (1 + \mu)} \quad (4.11)$$

The maximum possible operating range of the main string ($\Delta V_{mpp \text{ max}}$) occurs when the auxiliary-source factor reaches zero. By substituting $\mu = 0$ into (4.11), $\Delta V_{mpp \text{ max}}$ is expressed as a function of r , illustrated in Figure 22.

$$\Delta V_{mpp \text{ max}} = \frac{2 \cdot \eta_c}{2 \cdot r + \eta_c} \quad (4.12)$$

Figure 22 – Maximum possible operating range of the main string as a function of main-to-auxiliary PV ratio (r), assuming $\eta_c = 0.9$.



Source: Author

4.1.2 Static Gain Estimation

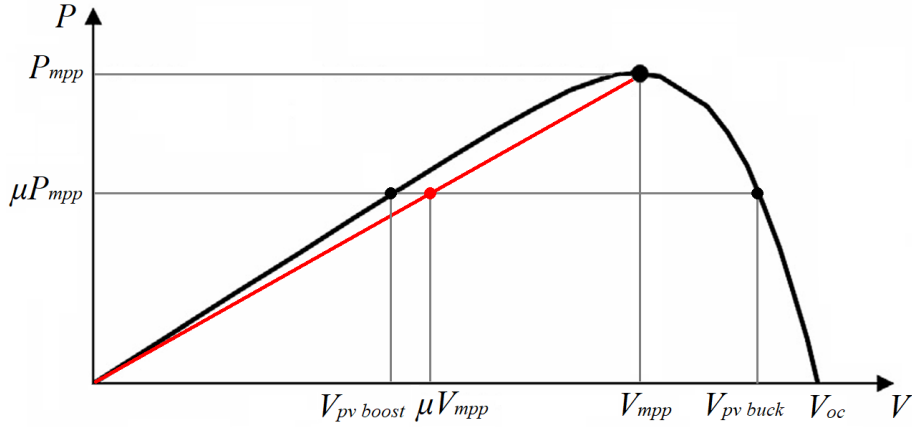
Since the converter's output voltage V_c and input power P_m can be expressed as functions of μ , the static gain G —formulated in general terms in Equation (4.13)—can likewise be represented as a function of μ .

$$G = \frac{V_{out}}{\eta_c \cdot V_{in}} \quad (4.13)$$

Due to the coupling relationship, the converter's input voltage (V_{in}) corresponds to the auxiliary string voltage (V_m), which varies with each operating power point according

to its characteristic curve, as shown in Figure 23. The red curve illustrates the ideal output voltage as a function of operating power. For each operating power level defined by $P_m = \mu \cdot P_{mpp}$, with $\mu < 1$, two corresponding values of PV voltage (V_{pv}) can be identified. The voltage $V_{pv \text{ boost}}$, which is lower than the output voltage, can only be attained using a step-up converter. Conversely, the voltage $V_{pv \text{ buck}}$, which exceeds the output voltage, requires a step-down converter.

Figure 23 – Typical P-V curve

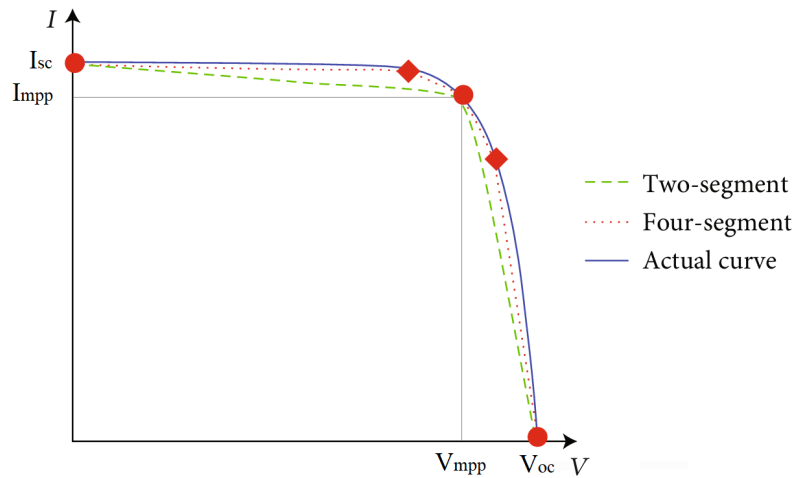


Source: Author

Although V_c can be precisely determined as a function of μ , V_m must be estimated using two key approximations: linearization of the current-voltage (I-V) curve, and adoption of constant proportionality factors throughout operation.

A two-segment linearization of the IV curve, illustrated in Figure 24, was considered using the proportionality constants K_I and K_V , defined in (4.14) and (4.15), respectively.

Figure 24 – Piecewise linearization of the I-V curve

Source: Modified from [Saraswathi et al. \(2022\)](#)

$$K_I = \frac{I_{sc \ stc}}{I_{mpp \ stc}} \quad (4.14)$$

$$K_V = \frac{V_{oc \ stc}}{V_{mpp \ stc}} \quad (4.15)$$

These constants relate the maximum power point (MPP) values to the open-circuit voltage and short-circuit current. Both K_I and K_V exhibit similar behavior, with only minor variation during PV cell operation (Katche et al., 2023) (Hart; Branz; Iii, 1984).

By expressing V_m as a function of μ and substituting it into Equation (4.13), the required gains G_{buck} e G_{boost} —corresponding to operation at $V_{pv \ buck}$ and $V_{pv \ boost}$, respectively—can be determined. The complete calculation is provided in Appendix B.

$$G_{buck} = \frac{\mu \cdot V_{mpp}}{V_{pv \ buck}} = \frac{2 \cdot \mu}{K_V + \sqrt{K_V^2 - 4 \cdot \mu \cdot (K_V - 1)}} \quad (4.16)$$

$$G_{boost} = \frac{\mu \cdot V_{mpp}}{V_{pv \ boost}} = \frac{2 \cdot \mu \cdot (1 - K_I)}{-K_I + \sqrt{K_I^2 + 4 \cdot \mu \cdot (1 - K_I)}} \quad (4.17)$$

$$D_{buck} = G_{buck} \quad (4.18)$$

$$D_{boost} = 1 - \frac{1}{G_{boost}} \quad (4.19)$$

4.1.3 Efficiency Evaluation

The overall performance of a photovoltaic MPPT system can be defined as the ratio of the power reaching the DC bus (P_{bus}) to the maximum available power (P_{mpp}) from all the PV components ($n + m$).

$$\rho_{syst} = \frac{P_{bus}}{(n + m) \cdot P_{mpp}} \quad (4.20)$$

In a coupled FRPP MPPT system, only the auxiliary string power is subject to converter efficiency (η_c), enabling the main string to operate at its maximum power without incurring converter losses. However, this requires removing the auxiliary string from its maximum power point, in accordance with the auxiliary-source factor (μ). Considering (4.5) and (4.20), the performance of the coupled FRPP MPPT (ρ_{cfrpp}) depends not only on converter's efficiency η_c , but also on factor μ and ratio r .

$$\rho_{cfrpp} = \frac{n \cdot P_{mpp} + \mu \cdot \eta_c \cdot m \cdot P_{mpp}}{(n + m) \cdot P_{mpp}} = \frac{r + \mu \cdot \eta_c}{r + 1} \quad (4.21)$$

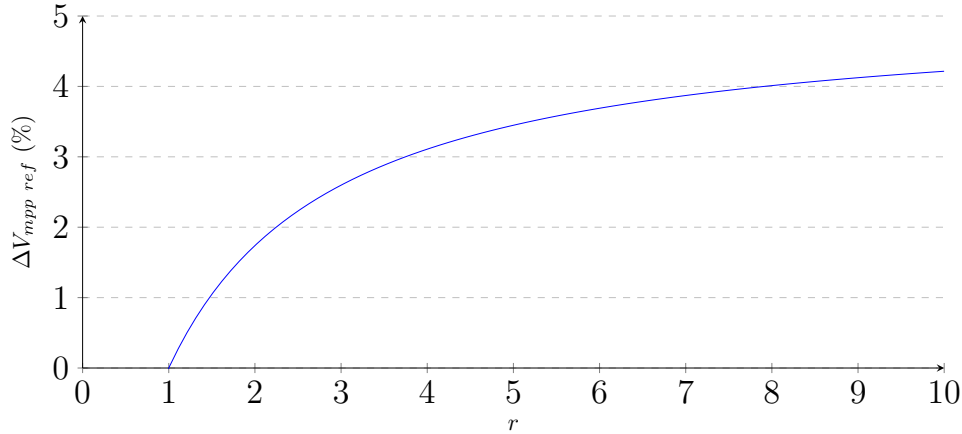
Thus, for the system to achieve a performance greater than a specific reference value (ρ_{ref}), it must not operate with a auxiliary-source factor below μ_{ref} . The value of μ_{ref} can be determined by substituting $\rho_{cfrpp} = \rho_{ref}$ into (4.21).

$$\mu_{ref} = \frac{\rho_{ref} \cdot (r + 1) - r}{\eta_c} \quad (4.22)$$

With μ_{ref} established, and substituting $\mu = \mu_{ref}$ into (4.11), and then applying (4.22), the reference operating range ($\Delta V_{mpp\ ref}$) is defined. Within this range, the system performance meets or exceeds the reference performance value ($\rho_{cfrpp} \geq \rho_{ref}$). $\Delta V_{mpp\ ref}$ is expressed as a function of r , illustrated in Figure 25.

$$\Delta V_{mpp\ ref} = \frac{2 \cdot (1 - \rho_{ref}) \cdot r - 2 \cdot \rho_{ref} + 2 \cdot \eta_c}{(1 + \rho_{ref}) \cdot r + \rho_{ref} + \eta_c} \quad (4.23)$$

Figure 25 – Reference operating range of the main string as a function of main-to-auxiliary PV ratio (r), assuming $\eta_c = 0.9$ and $\rho_{ref} = 0.95$.



Source: Author

Even though $\Delta V_{mpp\ ref}$ increases with r , the curve exhibits asymptotic behavior, allowing the limit to be calculated.

$$\lim_{r \rightarrow \infty} \Delta V_{mpp\ ref} = \frac{2 \cdot (1 - \rho_{ref})}{1 + \rho_{ref}} \quad (4.24)$$

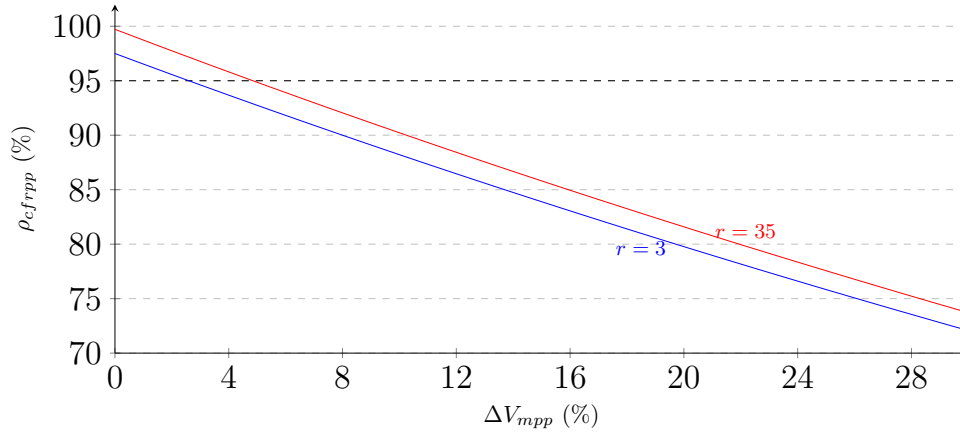
This is a limitation of the coupled FRPP architecture. For a given ρ_{ref} , the largest operating range is determined by (4.24), which is not influenced by the r nor η_c . For instance, assuming $\rho_{ref} = 95\%$ and applying to (4.24), the result will be 5.13%, which means that a coupled FRPP system can consistently achieve performance exceeding 95% only if the environment restricts V_{mpp} variation to at most 5.13%, under the assumption of an ideal converter. Conversely, if the environment causes V_{mpp} to vary by more than 5.13%, the system's performance will drop below 95% at certain maximum power points.

This relationship between operating range and system performance is inversely proportional. For larger operating ranges, μ must decrease, thereby reducing the power generated by the auxiliary string and, consequently, lowering overall system performance.

To express the system performance (ρ_{cfrpp}) as a function of ΔV_{mpp} for a given r and η_c , μ must be isolated in (4.11) and substituted into (4.21). The resulting function is (4.25) and it is illustrated in Figure 26.

$$\rho_{cfrpp} = \frac{(r + \eta_c) \cdot (1 - \Delta V_{mpp}/2)}{(r + 1) \cdot (1 + \Delta V_{mpp}/2)} \quad (4.25)$$

Figure 26 – Performance of the coupled FRPP system as a function of ΔV_{mpp} for $r = 35$ (red) and $r = 3$ (blue), assuming $\eta_c = 0.9$ and . A reference performance value, $\rho_{ref} = 0.95$, is highlighted.



Source: Author

Assuming an ideal converter efficiency ($\eta_c = 1$) and isolating ΔV_{mpp} in (4.25), the result coincides with (4.24), which highlights the intrinsic limitation of the architecture—even under ideal conditions.

4.1.4 System Designing

A PV system design with coupled FRPP must consider the climatic history of the region where the PV plant will be installed. This information, applied at the module level, defines the expected values for $V_{mpp\ low}$ and $V_{mpp\ high}$, and consequently, $\Delta V_{mpp\ max}$. With $\Delta V_{mpp\ max}$ defined and an estimated value for the converter efficiency η_c , the ratio r can be calculated by (4.12).

Since converter efficiency varies with load conditions, an average value is typically adopted for design purposes. However, when detailed efficiency curves are available, they can be incorporated into the design process to improve accuracy. The greater the available efficiency data, the more precise the FRPP architecture can be refined.

By knowing the total number of PV components ($n + m$) and the ratio r , the sizes of the main and auxiliary strings, n and m , are determined, and therefore, V_{bus} can be calculated using (4.8) or (4.9).

4.2 Simulation

The simulated circuit for the coupled FRPP architecture is shown in Figure 21, with twelve modules ($n + m = 864$ cells). For the wide-range scenario, three modules formed the auxiliary string ($m = 216$ cells) and the remaining formed the main string ($n = 648$ cells); that is, $r = 3$, connected to a constant voltage DC bus, $V_{bus} = 361$ V. For the narrow-range scenario, a submodule (a third of a module) served as the auxiliary string ($m = 24$ cells) and the rest forming the main string ($n = 840$ cells); that is, $r = 35$, connected to a constant voltage DC bus, $V_{bus} = 390$ V. The system was designed as explained in Section 4.1.4, considering $\eta_c = 97\%$ for the wide-range scenario and $\eta_c = 70\%$ for the narrow-range scenario.

The overall performance values, ρ_{syst} , calculated according to (4.20), were evaluated at each tested point for all architectures. To compare the overall operation, two averages were considered: a simple average, assuming each operating point is equally likely to occur during operation; and a weighted average, based on a normal distribution of the V_{mpp} values, where values closer to the mean occur more frequently, as presented in (Zientarski et al., 2017) (Zientarski et al., 2017).

Additionally, for the coupled FRPP, the auxiliary-source factor (μ) was verified, and both it and ρ_{cfrpp} were compared with the expected values calculated by (4.21) and (4.25) to validate the theoretical analysis.

The simulated operating points of the coupled FRPP are shown in Tables 8 and 9, with voltage in volts (V) and power in watts (W), corresponding to the wide- and narrow-range operating scenarios, respectively.

Table 8 – Operation and Performance of the Coupled FRPP PV System in the Wide-Range Scenario

p	ΔV_{mpp}	$V_{pv\ n}$	D	$n.P_{mpp}$	P_n	$m.P_{mpp}$	P_m	P_c	P_{loss}	P_{bus}	μ	η_c	ρ_{syst}
1	0.0%	30.4	1.00	2351.7	2351.3	783.9	783.7	755.5	28.2	3106.8	1.00	96.4%	99.1%
2	2.6%	31.2	0.80	2437.8	2437.8	812.6	728.0	699.6	28.4	3137.4	0.90	96.1%	96.5%
3	5.7%	32.2	0.67	2524.1	2524.1	841.4	653.0	625.1	27.9	3149.2	0.78	95.7%	93.6%
4	8.7%	33.1	0.56	2610.7	2610.7	870.2	577.1	550.1	27.0	3160.8	0.66	95.3%	90.8%
5	11.7%	34.1	0.46	2697.5	2697.5	899.2	499.6	474.0	25.6	3171.5	0.56	94.9%	88.2%
6	14.5%	35.1	0.35	2784.5	2784.5	928.2	422.3	398.3	24.0	3182.8	0.45	94.3%	85.7%
7	17.2%	36.1	0.29	2871.7	2871.7	957.2	342.3	320.1	22.2	3191.8	0.36	93.5%	83.4%
8	19.9%	37.1	0.22	2959.1	2959.1	986.4	263.1	242.6	20.5	3201.7	0.27	92.2%	81.1%
9	22.5%	38.0	0.15	3046.5	3046.5	1015.5	184.8	165.6	19.2	3212.1	0.18	89.6%	79.1%
10	25.0%	39.0	0.08	3134.1	3134.1	1044.7	104.3	86.0	18.3	3220.1	0.10	82.5%	77.1%
11	27.5%	40.1	0.02	3221.8	3221.8	1073.9	22.2	4.6	17.6	3226.4	0.02	20.7%	75.1%

Table 9 – Operation of the Coupled FRPP PV System in the Narrow-Range Scenario

p	ΔV_{mpp}	$V_{pv\ n}$	D	$n.P_{mpp}$	P_n	$m.P_{mpp}$	P_m	P_c	P_{loss}	P_{bus}	μ	η_c	ρ_{syst}
1	0.0%	32.8	0.99	3336.1	3336.0	95.3	95.3	66.4	28.9	3402.4	1.00	69.7%	99.2%
2	0.2%	32.8	0.82	3352.2	3352.2	95.8	86.1	59.6	26.5	3411.8	0.90	69.2%	99.0%
3	0.6%	33.0	0.62	3368.2	3368.2	96.2	69.5	45.7	23.8	3413.9	0.72	65.8%	98.5%
4	1.0%	33.1	0.46	3384.3	3384.3	96.7	52.6	31.2	21.4	3415.5	0.54	59.3%	98.1%
5	1.5%	33.3	0.31	3400.3	3400.3	97.2	36.3	17.1	19.2	3417.4	0.37	47.1%	97.7%
6	1.9%	33.4	0.16	3416.4	3416.4	97.6	19.8	2.7	17.1	3419.1	0.20	13.6%	97.3%

4.2.1 Validation

In general, the expected values for D , μ , and ρ_{syst} , were consistent with the simulations, as shown in Tables 10 and 11.

Table 10 – Comparison between Simulated and Calculated Values of the Coupled FRPP PV System in the Wide-Range Scenario

ΔV_{mpp}	D			μ			ρ_{syst}		
	Sim.	Calc.	Error	Sim.	Calc.	Error	Sim.	Calc.	Error
0.0%	1.00	1.00	0.00	1.00	1.00	0.00	99.1%	99.3%	0.17%
2.6%	0.80	0.87	0.07	0.90	0.89	0.00	96.5%	96.7%	0.15%
5.7%	0.67	0.73	0.06	0.78	0.77	0.00	93.6%	93.7%	0.15%
8.7%	0.56	0.61	0.05	0.66	0.66	0.01	90.8%	91.0%	0.15%
11.7%	0.46	0.49	0.03	0.56	0.55	0.01	88.2%	88.3%	0.13%
14.5%	0.35	0.40	0.05	0.45	0.45	0.01	85.7%	85.9%	0.14%
17.2%	0.29	0.30	0.01	0.36	0.35	0.01	83.4%	83.5%	0.13%
19.9%	0.22	0.22	0.00	0.27	0.26	0.01	81.1%	81.3%	0.14%
22.5%	0.15	0.15	0.00	0.18	0.17	0.01	79.1%	79.2%	0.14%
25.0%	0.08	0.07	0.01	0.10	0.09	0.01	77.1%	77.2%	0.13%
27.5%	0.02	0.01	0.01	0.02	0.01	0.01	75.1%	75.2%	0.13%
MAE			0.03			0.01			0.14%

Table 11 – Comparison between Simulated and Calculated Values of the Coupled FRPP PV System in the Narrow-Range Scenario

ΔV_{mpp}	D			μ			ρ_{syst}		
	Sim.	Calc.	Error	Sim.	Calc.	Error	Sim.	Calc.	Error
0.0%	0.99	1.00	0.01	1.00	1.00	0.00	99.2%	99.2%	0.01%
0.2%	0.82	0.88	0.06	0.90	0.91	0.01	99.0%	99.0%	0.04%
0.6%	0.62	0.64	0.02	0.72	0.69	0.03	98.5%	98.6%	0.02%
1.0%	0.46	0.42	0.04	0.54	0.48	0.07	98.1%	98.1%	0.03%
1.5%	0.31	0.23	0.08	0.37	0.26	0.11	97.7%	97.7%	0.03%
1.9%	0.16	0.04	0.12	0.20	0.05	0.15	97.3%	97.3%	0.03%
MAE			0.06			0.06			0.03%

The expected values for μ and ρ_{syst} were calculated using (4.11) and (4.25), respectively, assuming $\eta_c = 0.97$ for the wide-range scenario and $\eta_c = 0.70$ for the narrow-range scenario. The expected values for D were calculated by (4.16) and (4.18), using the calculated values for μ and assuming $K_V = 1.22$.

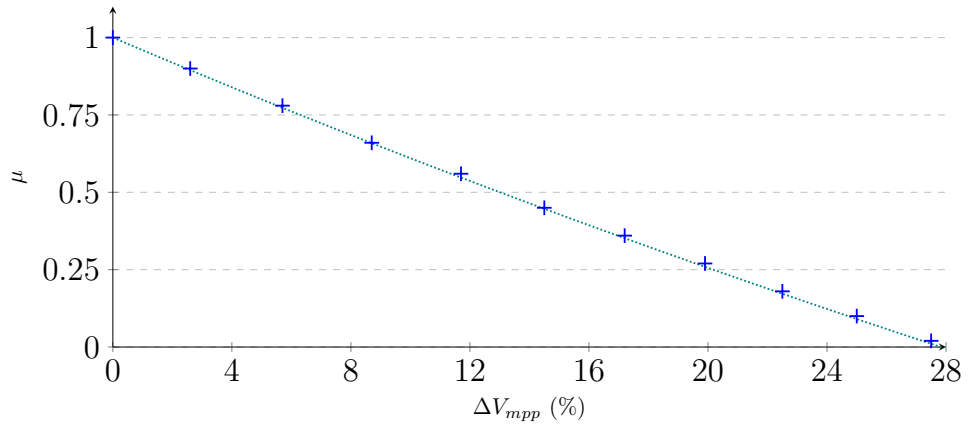
In the wide-range scenario, the low Mean Absolute Error (MAE) values were considered negligible, supporting the validity of the equations. In contrast, the slightly elevated MAE values for μ and D observed in the narrow-range scenario can be attributed

to the smaller value of m employed, which reduces the denominator in Equation (4.5). This reduction amplifies the sensitivity of μ , thereby affecting the accuracy of D calculations.

Figures 27 and 28 compare the values of μ obtained from simulation, marked by a cross (+), with those calculated using (4.11) (dotted line).

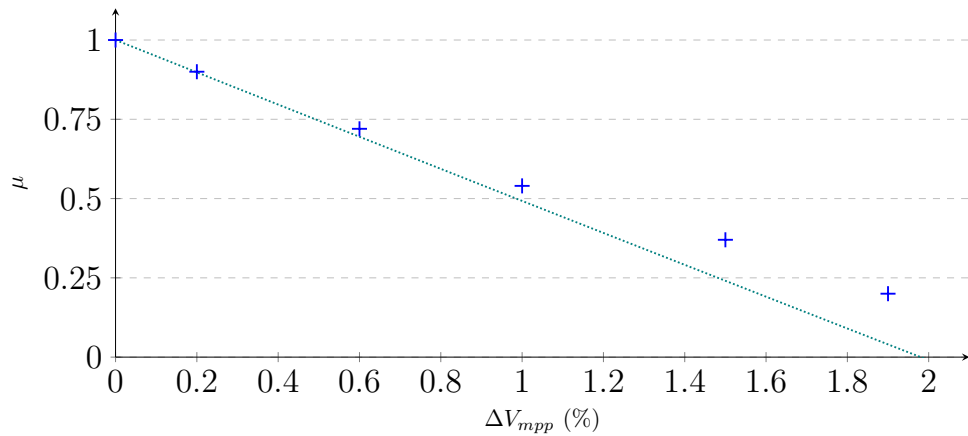
The assumption of different η_c values for the same converter was due to varying load conditions in each scenario. In the wide-range scenario, the auxiliary string has a nominal power of 990 W ($m = 216$), while in the narrow-range scenario, it is 110 W ($m = 24$). The variation in efficiency due to loading is also reflected in system operation: the higher the ΔV_{mpp} , the lower the μ and, consequently, the lower η_c . This also explains the discrepancy between the calculated and simulated values of μ , particularly at smaller magnitudes, as illustrated especially in Figure 28.

Figure 27 – Simulated (+) and calculated (dotted) values of μ for the wide-range scenario, assuming $\eta_c = 0.97$.



Source: Author

Figure 28 – Simulated (+) and calculated (dotted) values of μ for the narrow-range scenario, assuming $\eta_c = 0.7$.

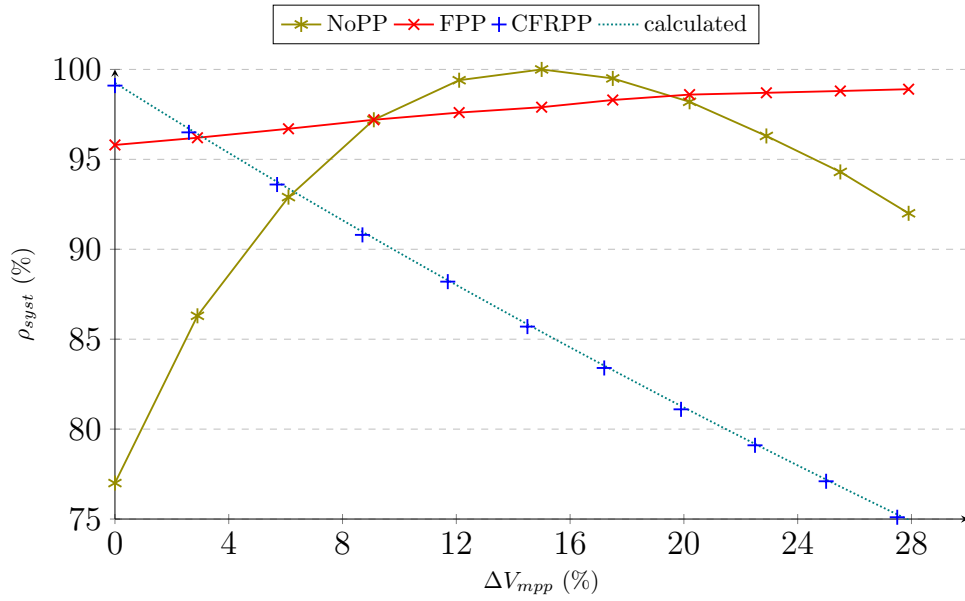


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4.2.2 Evaluation

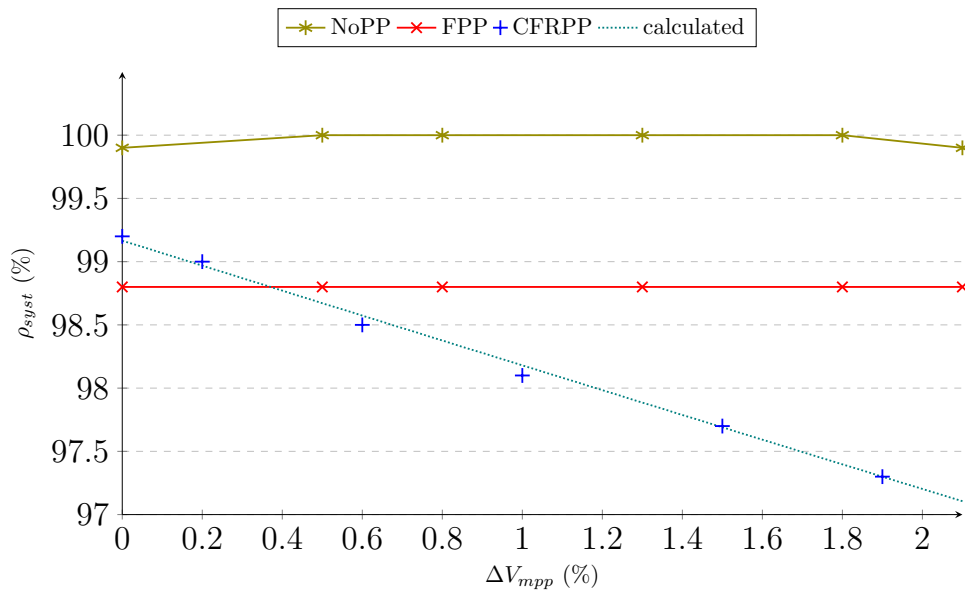
Figures 29 and 30 compare the performance of the three architectures in the wide-range and narrow-range scenarios, respectively. Both figures also show the expected performance of the coupled FRPP as a function of ΔV_{mpp} , calculated using (4.25) (dotted line), assuming $\eta_c = 0.97$ for the wide-range scenario and $\eta_c = 0.70$ for the narrow-range scenario.

Figure 29 – Performance comparison in the wide-range scenario.



Source: Author

Figure 30 – Performance comparison in the narrow-range scenario.



Source: Author

In the wide-range scenario, FPP presents the highest simple and weighted average performance values of 97.8% and 97.9%, respectively, and is able to maintain performance above 95% throughout the entire operating range. This is not the case for the coupled FRPP and NoPP architectures, whose simple and weighted average performance values are 85.6% and 85.7%, and 94.3% and 96.7%, respectively.

In the narrow-range scenario, NoPP presents the highest simple and weighted average performance value of 100%, since the bus voltage has been properly regulated to approximate the V_{mpp} values within that operating range and there are no losses due to power processing. Again, the coupled FRPP did not outperform FPP; their simple and weighted average performance values are 98.3% (CFRPP), and 98.8% (FPP), respectively.

The narrow-range scenario was intended to promote higher performance for the coupled FRPP. According to (4.24), $\Delta V_{mpp} = 2\%$ would yield performance exceeding $\rho_{ref} = 98\%$ throughout the interval—in the best case, that is, when $r \rightarrow \infty$. Considering $r = 35$, $\eta_c = 70\%$, and $\rho_{ref} = 98\%$, and applying (4.23), the coupled FRPP is expected to exceed $\rho_{ref} = 98\%$ only when $\Delta V_{mpp, ref} = 1.2\%$, as shown in Figure 30, further validating the equation.

4.3 Chapter Conclusion

Fractional processing enables converters designed for lower power levels to regulate the generation of higher-power systems, as it provides lower voltage levels across the switches and passive elements of the converter. The coupled FRPP architecture proved capable of performing MPPT over a given range, and the model equations proposed in this work were found to be valid. However, theoretical analysis and simulations suggest that its operation is limited when performance is considered.

The relationship between operating range and system performance is inversely proportional, as shown in Figures 26, 29 and 30. For larger operating ranges, μ must decrease significantly, thereby reducing the power generated by the auxiliary string and, consequently, lowering overall system performance.

In comparison with a centralized MPPT architecture and a direct bus-connected architecture, the coupled FRPP architecture performed worse than both across two different scenarios under very stable conditions—that is, identical temperature and irradiance conditions across all PV panels and no oscillations in V_{bus} . For the wide-range scenario ($\Delta V_{mpp} = 28\%$), the Full Power Processing architecture was preferred, and for the narrow-range scenario ($\Delta V_{mpp} = 2\%$), the No-Power Processing architecture performed better.

Therefore, besides educational purposes, no practical application of the coupled FRPP architecture had been identified until the publication of this study.

5 Decoupled Fractional Power Processing

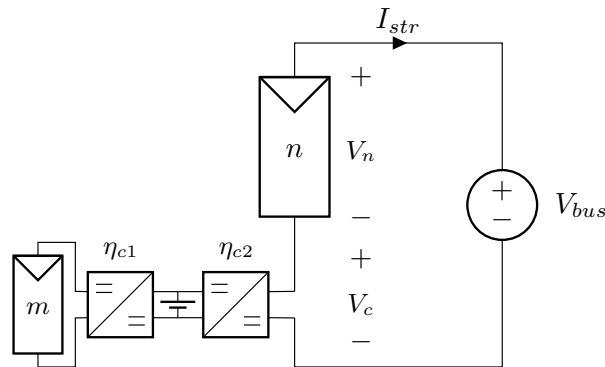
This chapter presents a novel investigation into how an FRPP architecture can be used as an MPPT for a PV system while using PV modules and an energy storage component as the auxiliary source (decoupled FRPP). Section 5.1 introduces the mathematical model that describes the operational principles of the proposed architecture. Section 5.2 details the simulation procedure, presents the corresponding results, validates the developed model, and assesses the performance of the architecture. Finally, Section 5.3 summarizes the key findings and conclusions drawn from this chapter.

5.1 Theoretical Analysis

For the following analyses, both the main and auxiliary strings are assumed to consist of panels of the same model, operating under identical temperature and irradiance conditions, ensuring a consistent maximum power point voltage and current (V_{mpp} and I_{mpp}) value across all panels.

The decoupled FRPP circuit is illustrated in Figure 31, which also includes some of the symbols needed to describe the system.

Figure 31 – Decoupled fractional power processing circuit.



Source: Author

5.1.1 MPPT range with a Decoupled Auxiliary Source

Considering that the purpose of the system is to ensure both the main and the auxiliary string reach their maximum power point (P_{mpp}), their operating power (P_n and P_m), and the main string current (I_{str}) and voltage (V_n) are defined by the following equations.

$$I_{str} = I_{mpp} \quad (5.1)$$

$$V_n = V_{bus} - V_c = n.V_{mpp} \quad (5.2)$$

$$P_n = V_n.I_{str} = n.P_{mpp} \quad (5.3)$$

$$P_m = m.P_{mpp} \quad (5.4)$$

To achieve (5.1) and (5.2) for varying values of V_{mpp} , the converter's output voltage (V_c) must adapt as the bus voltage (V_{bus}) remains fixed. As a result, the permissible range of V_{mpp} is directly linked to the operating range of V_c , which is influenced by the auxiliary source power (P_c). This, in turn, is related to the power of the auxiliary string (P_m), but is not limited to it, as the battery can also contribute with its power (P_{bat}), thereby making P_c not coupled to P_m and allowing both PV sources to reach their maximum power point. This decoupling relationship gives the source type and the architecture their defining names: Decoupled Auxiliary Source and Decoupled Fractional Power Processing.

$$P_c = V_c.I_{str} = \eta_{c2}.(\eta_{c1}.P_m + P_{bat}) \quad (5.5)$$

η_{c1} represents the efficiency of the first converter, that connects the auxiliary string to the battery, and η_{c2} , the efficiency of the second converter, that connects the battery to the main string, as depicted in Figure 3c.

The battery power (P_{bat}) can vary during system operation, even changing its flux, by absorbing and releasing power as needed. To represent P_{bat} in terms of the maximum available power of the auxiliary string ($P_{m\ mpp}$), the auxiliary-battery factor, β , is defined.

$$\beta = \frac{P_{bat}}{m.P_{mpp}} \quad (5.6)$$

By substituting (5.1), (5.4), and (5.6) into (5.5), a correlation can be established between the battery power and the operating range of V_c . With $\beta > 0$, the battery is discharging and providing power to the system, thereby increasing V_c . Conversely, with $\beta < 0$, the battery is charging and drawing power from the system, causing V_c to decrease.

$$V_c = \eta_{c2}.(\eta_{c1} + \beta).m.V_{mpp} \quad (5.7)$$

Based on (5.2) and (5.7), the range of values that V_{mpp} can assume may also be explicitly determined.

$$V_{mpp} = \frac{V_{bus}}{n + \eta_{c2}.(\eta_{c1} + \beta).m} \quad (5.8)$$

The operating range of the main string (ΔV_{mpp}) is defined as the difference between the highest and lowest V_{mpp} values, divided by the mean V_{mpp} value. In the decoupled FRPP architecture, the highest V_{mpp} value occurs when $V_c = 0$ and β is at its lowest ($\beta = -\eta_{c1}$), while conversely, the lowest V_{mpp} value is dependent on depends on the maximum value that β can reach.

$$V_{mpp\ high} = \frac{V_{bus}}{n} \quad (5.9)$$

$$V_{mpp\ low} = \frac{V_{bus}}{n + \eta_{c2} \cdot (\eta_{c1} + \beta) \cdot m} \quad (5.10)$$

$$\Delta V_{mpp} = \frac{V_{mpp\ high} - V_{mpp\ low}}{V_{mpp\ high} - (V_{mpp\ high} - V_{mpp\ low})/2} \quad (5.11)$$

It is important to highlight that in the DFRPP architecture, the voltage range ΔV_{mpp} is defined starting from $V_{mpp\ high}$, in contrast to the CFRPP, where the range begins at $V_{mpp\ low}$. This is because the output voltage V_c in DFRPP is only constrained by a minimum value ($V_c = 0$), whereas CFRPP imposes both lower and upper voltage limits. Defining the ΔV_{mpp} from $V_{mpp\ high}$ also guarantees that negative values of β —required for battery recharging—falls within the valid operating domain.

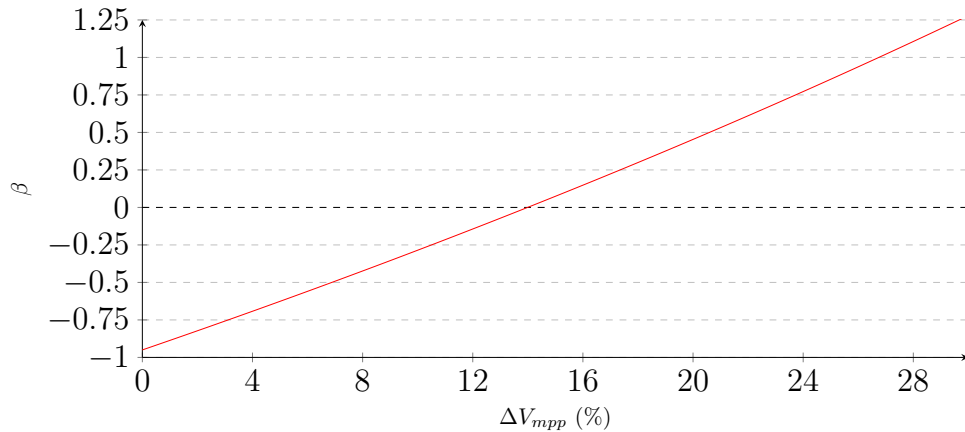
By applying (5.9) and (5.10) to (5.11), and applying r —that represent the ratio of the number of PV components in the main string to those in the auxiliary string ($r = n/m$), as described in (2.10)— ΔV_{mpp} is defined as a function of r , η_{c1} , η_{c2} and β .

$$\Delta V_{mpp} = \frac{2 \cdot \eta_{c2} \cdot (\eta_{c1} + \beta)}{2 \cdot r + \eta_{c2} \cdot (\eta_{c1} + \beta)} \quad (5.12)$$

By isolating β in (5.12), β can be described as a function of r , η_{c1} , η_{c2} and ΔV_{mpp} , illustrated in Figure 32.

$$\beta = \frac{r \cdot \Delta V_{mpp}}{\eta_{c2} \cdot (1 - \Delta V_{mpp}/2)} - \eta_{c1} \quad (5.13)$$

Figure 32 – Battery power factor β as a function of ΔV_{mpp} , assuming $\eta_{c1} = \eta_{c2} = 0.95$ and $r = 6$.



Source: Author

5.1.2 Static Gain Estimation

The battery voltage (V_{bat}) serves as both the output voltage of converter #1 and the input voltage of converter #2. Therefore, its value is a critical parameter for determining the required gains G_1 and G_2 of the respective converters.

Since the MPP voltage V_{mpp} can be expressed as function of β —demonstrated in (5.8)—the static gain G can likewise be represented as a function of β .

$$G_1 = \frac{V_{out}}{\eta_{c1} \cdot V_{in}} = \frac{V_{bat}}{\eta_{c1} \cdot m \cdot V_{mpp}} = \frac{V_{bat} \cdot (r + \eta_{c2} \cdot (\eta_{c1} + \beta))}{\eta_{c1} \cdot V_{bus}} \quad (5.14)$$

$$G_2 = \frac{V_{out}}{\eta_{c2} \cdot V_{in}} = \frac{V_{bus} - n \cdot V_{mpp}}{\eta_{c2} \cdot V_{bat}} = \frac{V_{bus} \cdot (\eta_{c1} + \beta)}{V_{bat} \cdot (r + \eta_{c2} \cdot (\eta_{c1} + \beta))} \quad (5.15)$$

For gain values $G \leq 1$, the duty cycle is determined using Equation (4.18). Conversely, for $G \geq 1$, the duty cycle is obtained from Equation (4.19).

$$D_{buck} = G \quad (5.16)$$

$$D_{boost} = 1 - \frac{1}{G} \quad (5.17)$$

5.1.3 Efficiency Evaluation

The overall performance of a photovoltaic MPPT system can be defined as the ratio of the power reaching the DC bus (P_{bus}) to the maximum available power (P_{mpp}) from all the PV components ($n + m$).

$$\rho_{syst} = \frac{P_{bus}}{(n + m) \cdot P_{mpp}} \quad (5.18)$$

In a decoupled FRPP MPPT system, only the auxiliary string and the battery are subject to converters efficiency (η_{c1} and η_{c2}), enabling the main string to operate at its maximum power without incurring converter losses. Considering (5.3), (5.4), (5.5), (5.6), and (5.18), the performance of the decoupled FRPP MPPT (ρ_{dfcpp}) is expressed depending on the converters' efficiency η_{c1} and η_{c2} , the factor β and the ratio r .

$$\rho_{dfcpp} = \frac{P_n + P_c}{(n + m) \cdot P_{mpp}} = \frac{r + \eta_{c2} \cdot (\eta_{c1} + \beta)}{r + 1} \quad (5.19)$$

For the system to work properly, it must be sized to maintain the battery state of charge (SOC) roughly the same over one day —neither charging nor discharging— so that by the end of the day, all the energy coming from the auxiliary string reaches the DC bus with no contribution from the battery.

As the battery adjust its power, according to β , to maintain the main string at its maximum power, the performance ρ_{dfcpp} may also fluctuate, even reaching instantaneous

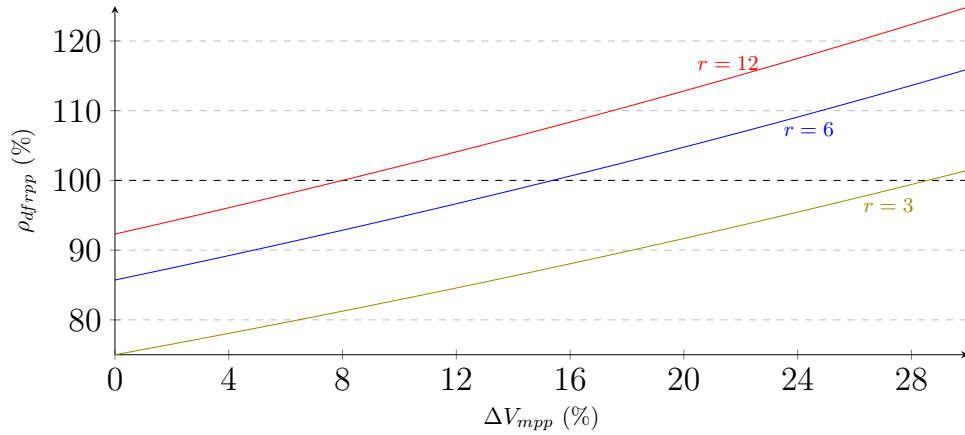
values above 100%, which happens when the battery provides power ($\beta > 0$), and the power reaching the DC bus exceeds the maximum powers available in the PV components $((n + m) \cdot P_{mpp})$.

Since the system must be sized to maintain the SOC over one day, the average auxiliary-battery factor over one day should be approximately zero. Then, the average performance over a full day can be calculated by applying $\beta = 0$ in (5.19), which serves as the performance metric to be evaluated.

To express the system performance as a function of ΔV_{mpp} for a given r , (5.13) must be substituted into (5.19). The resulting function is (5.20) and it is illustrated in Figure 33.

$$\rho_{dfrrpp} = \frac{r \cdot (1 + \Delta V_{mpp}/2)}{(r + 1) \cdot (1 - \Delta V_{mpp}/2)} \quad (5.20)$$

Figure 33 – Performance of the decoupled FRPP system as a function of ΔV_{mpp} , assuming $r = 3$ (yellow), $r = 6$ (blue), and $r = 12$ (red).



Source: Author

Excluding efficiency terms from the performance equation may lead to the mistaken impression that system behavior depends solely on r and ΔV_{mpp} . However, only a specific value of r guarantees long-term load balancing—essential for sustained operation. Converter efficiencies directly influence the amount of energy the battery can absorb or supply, making them critical in defining the appropriate ratio selection.

5.1.4 System Designing

A PV system design with decoupled FRPP must consider the climatic history of the region where the PV plant will be installed. This information, applied at the module level, defines the expected values for $V_{mpp \text{ low}}$ and $V_{mpp \text{ high}}$, and consequently, ΔV_{mpp} . With these values determined, and estimated values for the converter efficiencies η_{c1} and η_{c2} , the optimal r can be calculated.

Since converters efficiency varies with load conditions, an average value is typically adopted for design purposes. However, when detailed efficiency curves are available, they can be incorporated into the design process to improve accuracy. The greater the available efficiency data, the more precise the FRPP architecture can be refined.

The most challenging part of designing a decoupled FRPP system is defining an r results in a zero average β during operation. This can be roughly achieved by setting $\beta = 0$ at the mean V_{mpp} value. By applying $\beta = 0$ and using (5.9) in (5.8), and equating the result to $(V_{mpp \text{ high}} - V_{mpp \text{ low}})/\Delta V_{mpp}$ —with $\Delta V_{mpp} = (V_{mpp \text{ high}} - V_{mpp \text{ low}})/V_{mpp \text{ mean}}$, as explained in Section 5.1.1—the optimal r is defined by (5.21).

$$r = \frac{2 \cdot \eta_{c1} \cdot \eta_{c2}}{\Delta V_{mpp}} \quad (5.21)$$

This premise is roughly achieved, but not guaranteed, because there are some challenges in designing a system that maintains this equilibrium of charge, such as: the nonlinear relationship between β and ΔV_{mpp} ; the unpredictable environmental behavior, which causes each value of V_{mpp} to occur at different times throughout the day and year; the variation in the maximum available power P_{mpp} , meaning that $\beta = 0.1$ and $\beta = -0.1$ most likely correspond to different power values in watts; the variation in converter efficiency during operation; and the approximations required when choosing practical values for V_{bus} and r . Therefore, a decoupled FRPP system design must rely on reasonable assumptions, statistical data, and approximations.

By knowing the total number of PV components ($n + m$) and the ratio r , the sizes of the main and auxiliary strings, n and m , are determined, and therefore, V_{bus} can be calculated using (5.9).

The climatic history, together with the number of PV components m , provides insight into the expected power generation of the auxiliary string (E_m). The battery's charge capacity (E_{bat}) can be defined as half of E_m , which corresponds to the maximum amount of energy the system is capable of absorbing at a given moment—assuming charge balance is maintained throughout operation.

$$E_{bat} = \frac{E_m}{2} \quad (5.22)$$

The battery voltage (V_{bat}) is selected to minimize conduction losses in the switches, which are subjected to the maximum power point currents (I_{mpp}). Accordingly, a value near the maximum converter output voltage V_c is chosen, ensuring that the input current to converter #2 remains below or approximately equal to the expected I_{mpp} .

$$V_{bat} \approx V_{bus} - n \cdot V_{mpp \text{ low}} \quad (5.23)$$

5.2 Simulation

The simulated circuit for the decoupled FRPP architecture is shown in Figure 31, with twelve modules ($n + m = 864$ cells). One module and two submodules (two thirds of a module) served as the auxiliary string ($m = 120$ cells), connected to a 96 V battery by converter #1 ($c1$), that tracks the maximum power of the auxiliary string, and then connected to converter #2 ($c2$), that tracks the maximum power of the main string, formed by the rest of the modules ($n = 744$ cells); that is, $r = 6.2$, connected to a constant voltage DC bus, $V_{bus} = 414$ V. The system was designed as explained in Section 5.1.4, considering $\eta_{c1} = 92\%$ and $\eta_{c2} = 95\%$.

The overall performance values, ρ_{syst} , calculated according to (5.18), were evaluated at each tested point for all architectures. To compare the overall operation, two averages were considered: a simple average, assuming each operating point is equally likely to occur during operation; and a weighted average, based on a normal distribution of the V_{mpp} values, where values closer to the mean occur more frequently, as presented in (Zientarski et al., 2017) (Zientarski et al., 2017).

Additionally, for the decoupled FRPP, the auxiliary-battery factor (β) was verified, and both it and ρ_{drfpp} were compared with the expected values calculated by (5.19) and (5.20) to validate the theoretical analysis.

The simulated operating points of the decoupled FRPP are shown in Table 12, with voltage in volts (V) and power in watts (W).

Table 12 – Operation and Performance of the Decoupled FRPP PV System

p	ΔV_{mpp}	V_{pv}	n	D_1	D_2	$n.P_{mpp}$	P_n	$m.P_{mpp}$	P_m	P_{bat}	P_c	P_{bus}	β	η_{c1}	η_{c2}	ρ_{syst}
1	0.0%	40.0		1.35	0.02	3699.1	3699.1	596.6	596.5	-537.7	1.8	3700.9	-0.90	93.2%	9.8%	86.2%
2	2.5%	39.0		1.37	0.13	3598.4	3598.4	580.4	580.3	-428.4	93.0	3691.4	-0.74	93.0%	83.7%	88.3%
3	5.2%	38.0		1.38	0.24	3497.9	3497.9	564.2	564.1	-318.8	184.3	3682.2	-0.57	92.7%	90.3%	90.6%
4	7.7%	37.1		1.40	0.35	3397.5	3397.5	548.0	547.9	-211.0	273.7	3671.2	-0.39	92.5%	92.6%	93.0%
5	10.4%	36.1		1.41	0.46	3297.2	3297.2	531.8	531.7	-101.4	364.9	3662.1	-0.19	92.3%	93.8%	95.6%
6	13.2%	35.1		1.43	0.56	3197.1	3197.1	515.6	515.5	5.1	453.1	3650.2	0.01	91.9%	94.6%	98.3%
7	16.0%	34.1		1.45	0.67	3097.2	3097.2	499.5	499.4	110.2	540.6	3637.8	0.22	91.6%	95.2%	101.1%
8	18.9%	33.1		1.47	0.78	2997.5	2997.5	483.5	483.4	214.2	627.6	3625.1	0.44	91.4%	95.7%	104.1%
9	21.9%	32.1		1.49	0.89	2898.1	2898.1	467.4	467.3	317.5	714.0	3612.1	0.68	91.0%	96.1%	107.3%
10	25.0%	31.2		1.50	0.99	2799.0	2799.0	451.4	451.3	420.2	799.5	3598.5	0.93	90.7%	96.4%	110.7%
11	28.0%	30.2		1.52	1.10	2700.1	2700.1	435.5	435.4	526.3	881.8	3581.9	1.21	90.3%	95.9%	114.2%

Table 13 – Comparison between Simulated and Calculated Values of the Decoupled FRPP PV System in the Wide-Range Scenario

ΔV_{mpp}	Sim.	D_1 Calc.	Error	Sim.	D_2 Calc.	Error	Sim.	β Calc.	Error	Sim.	ρ_{syst} Calc.	Error
0.0%	1.35	1.36	0.01	0.02	0.00	0.02	-0.90	-0.92	0.02	86.2%	86.1%	0.04%
2.5%	1.37	1.38	0.01	0.13	0.11	0.02	-0.74	-0.75	0.01	88.3%	88.3%	0.02%
5.2%	1.38	1.39	0.01	0.24	0.23	0.01	-0.57	-0.57	0.00	90.6%	90.7%	0.09%
7.7%	1.40	1.41	0.01	0.35	0.34	0.01	-0.39	-0.40	0.01	93.0%	93.0%	0.04%
10.4%	1.41	1.42	0.01	0.46	0.45	0.01	-0.19	-0.20	0.01	95.6%	95.6%	0.05%
13.2%	1.43	1.44	0.01	0.56	0.56	0.00	0.01	0.00	0.01	98.3%	98.3%	0.06%
16.0%	1.45	1.46	0.01	0.67	0.67	0.00	0.22	0.22	0.00	101.1%	101.1%	0.03%
18.9%	1.47	1.47	0.00	0.78	0.78	0.00	0.44	0.44	0.00	104.1%	104.1%	0.07%
21.9%	1.49	1.49	0.00	0.89	0.90	0.01	0.68	0.68	0.00	107.3%	107.3%	0.05%
25.0%	1.50	1.50	0.00	0.99	1.01	0.02	0.93	0.94	0.01	110.7%	110.7%	0.02%
28.0%	1.52	1.52	0.00	1.10	1.10	0.00	1.21	1.21	0.00	114.2%	114.2%	0.06%
MAE			0.01			0.01			0.01			0.05%

5.2.1 Validation

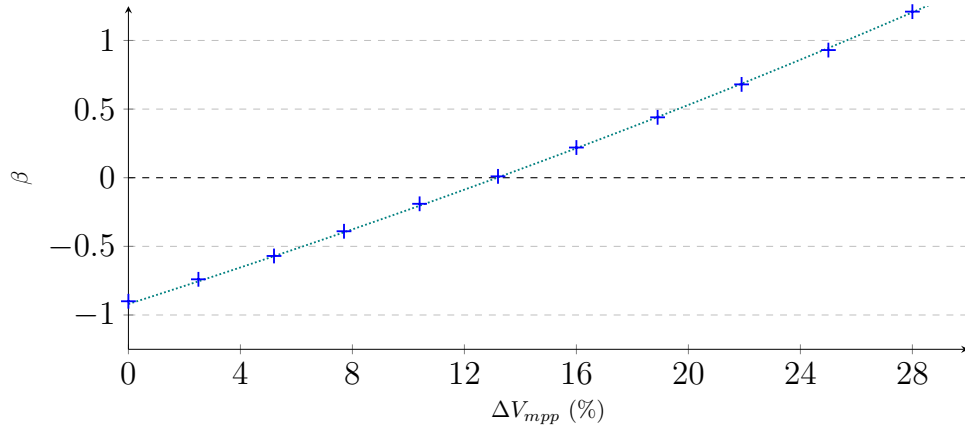
The expected values for D_1 , D_2 , β , and ρ_{syst} , as a function of ΔV_{mpp} , were consistent with the simulations, as shown in Table 13.

The expected values for β and ρ_{syst} were calculated using (5.13) and (5.20), respectively, assuming $\eta_{c1} = 0.92$ and $\eta_{c2} = 0.95$ for the wide-range scenario. The expected values for D_1 and D_2 were calculated by (5.14) and (5.15), using the calculated values for β , and then applying (5.16), (5.17), (3.12), and (3.13).

The low Mean Absolute Error (MAE) values were considered negligible, supporting the validity of the equations. Figure 34 compares the values of β obtained from simulation, marked by a cross (+), with those calculated using (5.13) (dotted line).

By taking the simple and weighted averages of P_{bat} and dividing them by the corresponding simple and weighted averages of $m.P_{mpp}$, the simple and weighted averages of β are obtained—both equal to zero ($\beta = 0.00$). Specifically at the mean V_{mpp} value, β was practically null ($\beta = 0.01$). Both of these outcomes validate (5.21) and lead to the conclusion that the system was properly designed and the battery charge is roughly balanced.

Figure 34 – Simulated (+) and calculated (dotted) values of β for the wide-range scenario, assuming $\eta_{c1} = 0.92$ and $\eta_{c2} = 0.95$.



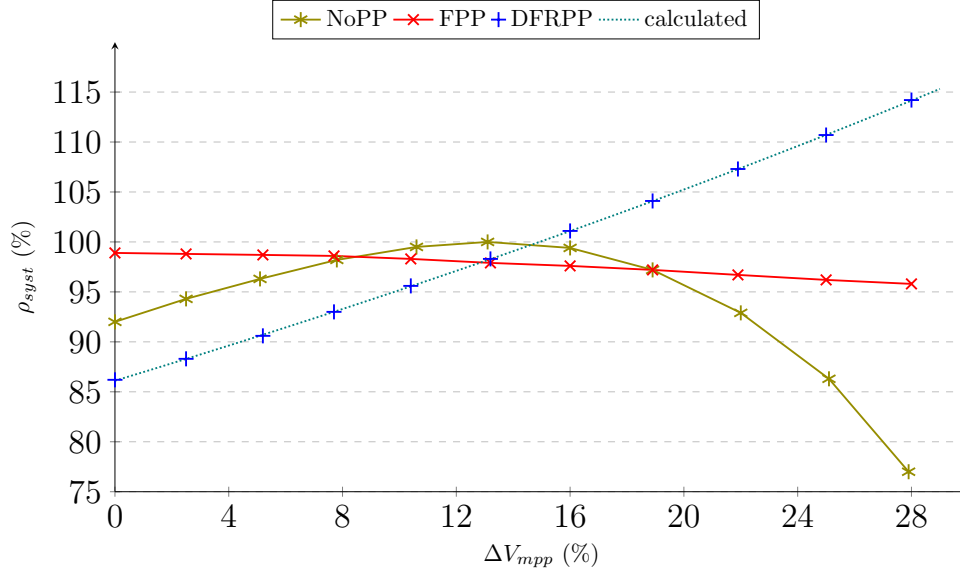
Source: Author

5.2.2 Evaluation

Figure 35 compares the performance of the three simulated architectures. It also show the expected performance of the decoupled FRPP as a function of ΔV_{mpp} , calculated using (5.20) (dotted line).

The ρ_{dfrrp} values obtained from simulation match almost perfectly with the calculated values. The variation in converter efficiency due to loading does not affect this metric, since it depends only on r and ΔV_{mpp} , as pointed out in (5.20).

Figure 35 – Performance comparison between architectures.



Source: Author

The decoupled FRPP presents the highest average performance value of 98.2%—the same for both simple and weighted averages—outperforming the FPP and NoPP architectures, whose simple and weighted average performance values are 97.8% and 97.9%, and 94.3% and 96.7%, respectively.

The theoretical average performance for the decoupled FRPP, calculated by applying $\beta = 0$ in (5.19), as explained in Section 5.1.3, is also validated, since the resulting value, with $r = 6.2$ and assuming $\eta_{c1} = 0.92$ and $\eta_{c2} = 0.95$, is $\rho_{dfrrpp} = 98.3\%$.

As explained in Section 5.1.3, the instantaneous performance of the decoupled FRPP does not provide meaningful insight into the system, since it varies according to the operation of the battery, which either supplies or absorbs power, making the average performance the appropriate metric for comparison.

It is important to highlight that, in addition to outperforming the other architectures, the converters of the decoupled FRPP process only 13.9% of the total system power—obtained by applying $r = 6.2$ in (2.11)—so they can be designed to be smaller and potentially even cheaper.

5.3 Chapter Conclusion

Fractional processing enables converters designed for lower power levels to regulate the generation of higher-power systems, as it provides lower voltage levels across the switches and passive elements of the converter. The decoupled FRPP architecture proved capable of performing MPPT over a given range, with high overall performance, while

using converters rated for a fraction of the total system power. The model equations proposed in this work were found to be valid, and the simulated decoupled FRPP PV system exhibited an average performance of 98.2%, with converters processing only 13.9% of the total system power.

In comparison with a centralized MPPT architecture and a direct bus-connected architecture, the decoupled FRPP architecture outperformed both, albeit under very stable conditions—that is, identical temperature and irradiance across all PV panels and no oscillations in V_{bus} .

However, this architecture requires two converters and an energy storage element, which increases the costs of acquisition, installation, and maintenance. Nevertheless, the converters are low-power, and the energy storage element can serve additional functions, such as providing virtual inertia and storing surplus generation.

Another challenge lies in system design, which must rely on reasonable assumptions, statistical data, and approximations to correctly size the system and maintain charge equilibrium in the battery over a daily cycle.

Therefore, the decoupled FRPP is recommended for MPPT applications where high efficiency or low-power converters are needed, particularly at sites with reliable climatic records to support proper system design.

6 Conclusion

Partial power processing has been a widely researched topic due to its potential to improve the overall efficiency of systems while using components designed for lower power, thereby reducing the cost and size of electronics. Given these characteristics, the use of partial and differential power converters in photovoltaic systems—as maximum power point tracking methods—is widespread in the literature. With this in mind, this study aimed to address the knowledge gap surrounding a third, less-explored architecture: the fractional power processing (FRPP).

The literature review revealed few studies related to FRPP, most of which focused on battery charging systems, and no mathematical models were found that explain how this architecture could be used as an MPPT method for photovoltaic systems. Due to the lack of extensive research on the topic, inconsistencies in nomenclature were observed in the literature, with different terms used to refer to FRPP—and “fractional” sometimes used to describe a specific converter topology unrelated to FRPP. This work also attempted to contribute to the clarification of terminology related to FRPP, helping to avoid misunderstandings.

In light of this, the main contribution of this study is the proposal of two approaches for using FRPP as an MPPT method: the coupled and decoupled FRPP architectures. For each proposed architecture, mathematical modeling was carried out, accompanied by theoretical analysis that helps elucidate the systems’ capabilities and limitations, as well as their performance compared to other power processing methods.

To validate the equations and evaluate the performance of the two proposed systems, simulations were performed using PSIM software. As a result, all model equations proposed in this work were found to be valid.

It is concluded that fractional power processing enables converters designed for lower power levels to regulate the generation of higher-power systems, as it provides lower voltage levels across the switches and passive elements of the converter. When applied to photovoltaic systems, both types of FRPP have demonstrated the ability to achieve maximum power while using low-power, low-complexity converters, since they are non-isolated and can even adopt simple topologies, such as buck or boost. However, each type exhibited significantly different capabilities.

The coupled FRPP architecture proved capable of performing MPPT over a given range, however, theoretical analysis and simulations suggest that its operation is limited when performance is considered, because the relationship between its operating range and system performance is inversely proportional. For larger operating ranges, the auxiliary-

source factor (μ) must decrease significantly, thereby reducing the power generated by the auxiliary string and, consequently, lowering overall system performance.

In comparison with a centralized MPPT architecture and a direct bus-connected architecture, the coupled FRPP architecture performed worse than both across two different scenarios under very stable conditions—that is, identical temperature and irradiance conditions across all PV panels and no oscillations in V_{bus} . For the wide-range scenario ($\Delta V_{mpp} = 28\%$), the Full Power Processing architecture was preferred, and for the narrow-range scenario ($\Delta V_{mpp} = 2\%$), the No-Power Processing architecture performed better. Therefore, except for educational purposes, no practical application of the coupled FRPP architecture had been identified until the publication of this study.

On the other hand, the decoupled FRPP architecture proved capable of performing MPPT over a given range, with high overall performance. The simulated decoupled FRPP PV system exhibited an average performance of 98.2%, with converters processing only 13.9% of the total system power, in a wide-range scenario ($\Delta V_{mpp} = 28\%$). In comparison with a centralized MPPT architecture and a direct bus-connected architecture, the decoupled FRPP architecture outperformed both, albeit under the same very stable conditions already mentioned.

However, this architecture requires two converters and an energy storage element, which increases the costs of acquisition, installation, and maintenance. Nevertheless, the converters are low-power, and the energy storage element can serve additional functions, such as providing virtual inertia and storing surplus generation. Another challenge lies in system design, which must rely on reasonable assumptions, statistical data, and approximations to correctly size the system and maintain charge equilibrium in the battery over a daily cycle. Therefore, the decoupled FRPP is recommended for MPPT applications where high efficiency or low-power converters are needed, particularly at sites with reliable climatic records to support proper system design.

In general, both types of FRPP can be used as MPPT methods, although only the decoupled type is capable of delivering performance gains compared to the classical power processing architectures: FPP and NoPP.

6.1 Conference Publications

Derived from this dissertation, two papers were presented and published at the 18th Brazilian Power Electronics Conference (COBEP 2025):

- LEÃO, A. S. L. F.; CRIVELLARI, A. L. S. ; SANTOS, W. M.; MPPT for PV Systems using the Coupled Fractional Power Processing Architecture. *18th Brazilian Power Electronics Conference (COBEP 2025)*.

- LEÃO, A. S. L. F.; CRIVELLARI, A. L. S. ; SANTOS, W. M.; MPPT for PV Systems using the Decoupled Fractional Power Processing Architecture. *18th Brazilian Power Electronics Conference (COBEP 2025)*.

6.2 Future Work

Based on the contributions of this study, the following research directions are proposed:

- Run experimental tests of the Fractional Power Processing Architecture as an MPPT method and evaluate its capabilities in a more practical scenario.
- Run simulations of the Fractional Power Processing Architecture as an MPPT method under a more realistic scenario, using a proper distribution of irradiance and temperature during the year, for evaluating power generation. This study emulates the voltage operating range as a proof of concept, using irradiance and temperature profiles that are not suitable for evaluating annual power generation.
- Analyze the Fractional Power Processing Architecture applied to a PV system under partial-shading and other non-ideal scenarios. This study considers both the main and auxiliary strings to consist of panels of the same model, operating under identical temperature and irradiance conditions.
- Analyze the Fractional Power Processing Architecture applied to a PV system considering different—or even reconfigurable—interconnections for both the main and auxiliary photovoltaic arrays. This study considers only string configurations as the array form for both the main and auxiliary sources.
- Investigate the functioning and capabilities of a Fractional Power Processing Architecture using a partial power converter. This study considers only a full power converter as the controller for the auxiliary source.
- Analyze the Decoupled Fractional Power Processing Architecture considering a battery model that accounts for energy losses. This study models the battery as a voltage source only.
- Investigate the functioning and capabilities of a theoretical third type of Fractional Power Processing Architecture applied to a PV system: the non-coupled FRPP, consisting solely of an ESS as the auxiliary source, which would be charged by the main PV source. It would be similar to a decoupled FRPP, but without an auxiliary PV source, thereby eliminating the concept of coupling.

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APPENDIX A – Converter Design

The four-switch buck–boost converter employed in this study is based on a prototype photovoltaic optimizer—a buck converter—owned by the author and intended for future experimental tests in FRPP applications. Accordingly, the inductance and capacitance parameters were selected to approximate those of the prototype. Additionally, the assumed thermal resistance of 3 °C/W for each MOSFET reflects the expected thermal resistance of the heat sink model HS 12552 used in the prototype.

To enable a fair comparison between the proposed architectures, the same converter was deliberately applied across varying power levels and operating voltages. As a result, the design does not meet voltage and current ripple specifications in all configurations.

Nevertheless, this limitation is not critical to the scope of the present work. Due to its synchronous topology, the converter avoids discontinuous operation and is considered suitable for validating the conceptual framework introduced in this research.

A.1 Switch Selection

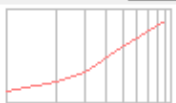
Maximum switch current equivalent to simulation maximum short-circuit current:

$$I_{max} = I_{sc_stc} \cdot (1 + 0.00053 \cdot (75 - 25)) = 9.7 \text{ A}$$

Maximum switch voltage equivalent to simulation maximum open-circuit voltage:

$$V_{max} = V_{oc_stc} \cdot (1 + 0.0031 \cdot (25 - 5)) = 48.4 \text{ V}$$

Figure 36 – Electrical characteristics of the MOSFET IRFP460, used in PSIM simulations.

Manufacturer International Rectifier		Part Number IRFP460	
Package Discrete (n channel)		Style	
Absolute Maximum Ratings			
VDS,max (V):	500	ID,max (A):	20
		Tj,max (oC):	150
Electrical Characteristics - Transistor			
Test Conditions:		Test Conditions:	
RDS(on) (ohm):	0.27	VGS:	10
		ID:	12
VGS(th) (V):	3	ID:	0.00025
gfs (S):	13	VDS:	50
		ID:	12
tr (ns):	59	VDS:	250
tf (ns):	58	ID:	20
		RG (ohm):	4.3
Qg (nC):	210	Qgs (nC):	29
Qgd (nC):	110	Ciss (pF):	4200
		Coss (pF):	870
		Crss (pF):	350
		VDS:	25
		VGS:	0
		Freq. (MHz):	1
Note: In all "Test Conditions", VDS and VGS are in volt, and ID is in ampere.			
Electrical Characteristics - Diode			
Vd vs. IF Edit		Test Conditions:	
		trr (ns):	570
		Qrr (uC):	5.7
		IF (A):	20
		di/dt (A/us):	100
		TJ (oC):	25

Source: Author

A.2 Inductor and Capacitor Selection

L and C were sized for a buck converter powered by a CS6U-330P photovoltaic module, as used in the simulations. The component calculations were based on design guidelines from Hauke (2015).

Input Values for L calculation

$$f_s = 20 \text{ kHz}$$

$$I_{out \text{ max}} = 9.7 \text{ A}$$

$$\Delta I_L = 0.4 \cdot I_{out \text{ max}} = 3.88 \text{ A}$$

$$V_{out} = 17.55 \text{ V}$$

$$\Delta V_{out} = 0.02 \cdot 17.55 = 0.35 \text{ V}$$

Input voltage equivalent to the simulation mean MPP voltage:

$$V_{in} = 35.1 \text{ V}$$

Input voltage equivalent to half of the input voltage, since a duty cycle of $D = 0.5$ results in the maximum current ripple in the buck converter:

$$V_{out} = 0.5 \cdot 35.1 = 17.55 \text{ V}$$

$$L = \frac{V_{out} \cdot (V_{in} - V_{out})}{\Delta I_L \cdot f_s \cdot V_{in}} = 113.1 \text{ } \mu H$$

Selected inductance: $L = 100 \text{ } \mu H$

Input Values for C calculation

$$f_s = 20 \text{ kHz}$$

$$I_{out \text{ max}} = 9.7 \text{ A}$$

$$\Delta I_L = 0.4 \cdot I_{out \text{ max}} = 3.88 \text{ A}$$

$$V_{out} = 17.55 \text{ V}$$

$$\Delta V_{out} = 0.02 \cdot 17.55 = 0.35 \text{ V}$$

$$C_{out} = \frac{\Delta I_L}{8 \cdot f_s \cdot \Delta V_{out}} = 69.1 \text{ } \mu F$$

Selected capacitor: $C_{out} = C_{in} = 100 \text{ } \mu F$

APPENDIX B – Gain Calculation

The linearized I–V curve consists of two distinct segments: the first spanning from 0 to V_{mpp} , referred to as “boost region”, and the second from V_{mpp} to V_{oc} , referred to as “buck region”.

B.1 Boost Region

For $0 \leq v \leq V_{mpp}$, the current equation is defined by (B.1).

$$i = (1 - K_I) \cdot \frac{I_{mpp}}{V_{mpp}} \cdot v + K_I \cdot I_{mpp} \quad (\text{B.1})$$

Multiplying (B.1) by v to determine the power equation (B.2).

$$p = v \cdot i = (1 - K_I) \cdot \frac{I_{mpp}}{V_{mpp}} \cdot v^2 + K_I \cdot I_{mpp} \cdot v \quad (\text{B.2})$$

Considering $p = \mu \cdot P_{mpp}$, v as a function of μ can be determined.

$$\begin{aligned} \mu \cdot V_{mpp} &= \frac{(1 - K_I) \cdot v^2}{V_{mpp}} + K_I \cdot v \\ \mu \cdot V_{mpp}^2 &= (1 - K_I) \cdot v^2 + K_I \cdot v \cdot V_{mpp} \\ v &= \frac{-K_I V_{mpp} \pm \sqrt{K_I^2 V_{mpp}^2 - 4(1 - K_I)(-\mu V_{mpp}^2)}}{2(1 - K_I)} \\ V_{pv \text{ boost}} &= \frac{-K_I + \sqrt{K_I^2 + 4\mu(1 - K_I)}}{2(1 - K_I)} \cdot V_{mpp} \end{aligned} \quad (\text{B.3})$$

By applying (B.3) into (4.13), (4.17) is obtained.

B.2 Buck Region

For $V_{mpp} \leq v \leq V_{oc}$, the current equation is defined by (B.4).

$$i = \frac{1}{(1 - K_V)} \cdot \frac{I_{mpp}}{V_{mpp}} \cdot (v - V_{mpp}) + I_{mpp} \quad (\text{B.4})$$

Multiplying (B.4) by v to determine the power equation (B.5).

$$p = v \cdot i = \frac{1}{1 - K_V} \cdot \frac{I_{mpp}}{V_{mpp}} (v - V_{mpp}) \cdot v + I_{mpp} \cdot v \quad (\text{B.5})$$

Considering $p = \mu \cdot P_{mpp}$, v as a function of μ can be determined.

$$\begin{aligned}
 \mu \cdot V_{mpp} &= \frac{1}{1 - K_V} \left(\frac{v^2}{V_{mpp}} - v \right) + v \\
 \mu \cdot V_{mpp}^2 &= \frac{v^2}{1 - K_V} + \left(1 - \frac{1}{1 - K_V} \right) \cdot V_{mpp} \cdot v \\
 v &= \frac{-(1 - \frac{1}{1 - K_V}) \pm \sqrt{(1 - \frac{1}{1 - K_V})^2 + 4 \cdot \frac{1}{1 - K_V} \cdot \mu}}{2/(1 - K_V)} \cdot V_{mpp} \\
 V_{pv \text{ buck}} &= \frac{K_V + \sqrt{K_V^2 - 4 \cdot \mu \cdot (K_V - 1)}}{2} \cdot V_{mpp}
 \end{aligned} \tag{B.6}$$

By applying (B.6) into (4.13), (4.16) is obtained.