

Optimal Power Flow in Electrical Networks under Curtailment Scenarios

Giuseppe Schmuck Zanatta

Dissertation presented to the School of Technology and Management of Bragança to obtain the Master Degree in Renewable Energies and Energy Efficiency.

Work oriented by:

Prof. Dra. Ângela P. Ferreira

Prof. Dr. Ulisses Chemin Netto

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Dedication

To Laszlo Schmuck, Elizabeth Schmuck, Victor Zanatta, and Maria Aparecida Fabri Zanatta. You have inspired me beyond belief.

Acknowledgement

First of all, I'd like to express my deepest gratitude to my Creator and His crooked lines. Through the path chosen for me, I have found the things I have prayed for, even when His motives remain beyond my comprehension. For that, I am forever grateful.

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Abstract

In the context of the global energy transition, the utilization of renewable energies has experienced a significant rise over the past decade. However, the intermittent nature of renewable generators, particularly wind and photovoltaic sources, presents a considerable operational challenge for electrical system operators. Because of this, ensuring minimal energy curtailment rates becomes an important concern, and the implementation of energy storage systems, specifically Pumped Hydro Storage (PHS), emerges as a promising solution.

This research focuses on proposing a comprehensive model and operation framework for PHS and subsequently undertaking an in-depth analysis of the impact of integrating this PHS system into an electrical network. The analysis employs an optimal power flow formulation that is designed to minimize transmission losses while complying with operational constraints and curtailment requirements imposed by European legislation.

The findings of this study indicate that the implementation of the PHS system results in a substantial reduction in Renewable Energy Curtailment (REC), with improvements reaching up to 35.9%. Moreover, the integration of PHS also leads to a corresponding decrease in transmission losses of up to 2.21% for yearly simulations. These results highlight the effectiveness of incorporating PHS as a viable means of mitigating curtailment and transmission losses within the renewable energy framework.

Keywords: Optimal power flow, Pumped hydro storage, Renewable energy curtailment, Power systems

Resumo

No contexto da transição energética global, a utilização de energias renováveis tem demonstrado um aumento significativo na última década. No entanto, a natureza intermitente dos geradores renováveis, particularmente as fontes eólica e fotovoltaica, apresenta um desafio operacional considerável para os operadores do sistema elétrico. Por conta disso, garantir taxas mínimas de corte de energia torna-se uma preocupação importante, e a implementação de sistemas de armazenamento de energia, especificamente o Armazenamento Hidrelétrico Bombeado (PHS), emerge como uma solução promissora.

Esta pesquisa concentra-se em propor um modelo e um quadro operacional para o PHS e, posteriormente, realizar uma análise aprofundada do impacto da integração desse sistema de PHS em uma rede elétrica. A análise utiliza uma formulação de fluxo ótimo de potência que é implementada para minimizar as perdas de transmissão, ao mesmo tempo em que cumpre com as restrições operacionais e os requisitos de redução impostos pela legislação europeia.

Os resultados deste estudo indicam que a implementação do sistema de PHS resulta em uma redução substancial no Corte de Energia Renovável (REC), com melhorias de até 35,9%. Além disso, a integração do PHS também leva a uma diminuição nas perdas de transmissão em até 2,21% para simulações anuais. Esses resultados destacam a eficácia da incorporação do PHS como um meio viável de mitigar os cortes e as perdas de transmissão dentro do quadro de energia renovável.

Palavras-chave: Fluxo ótimo de potência, Armazenamento hidrelétrico bombeado, Cortes de energia renovável, Sistemas de potência.

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Acronyms

AC Alternating Current.

DC Direct Current.

ESS Energy Storage Systems.

GA Genetic Algorithm.

OPF Optimal Power Flow.

PF Power Flow.

PHS Pumped Hydro Storage.

REC Renewable Energy Curtailment.

RES Renewable Energy Sources.

Symbols

B Susceptance.

G Conductance.

I Current.

J Jacobian.

P Active Power.

Q Reactive Power.

S Apparent Power.

V Voltage.

Y Admittance.

ΔP Active Power Variation.

ΔQ Reactive Power Variation.

δ Phase Angle.

ϵ Convergence Precision.

f Mathematical Function.

n Number of buses.

x Mathematical Variable.

Chapter 1

Introduction

The transition towards cleaner and more sustainable energy sources has emerged as a key priority for various stakeholders in recent years. Governments, society, and the private sector are all recognizing the need for an energy transition, characterized by a swift shift from conventional non-renewable energy sources towards renewable alternatives. As we progress further into the 21st century, the energy landscape is undergoing rapid transformations, with an increasingly evident penetration of Renewable Energy Sources (RES) into electrical networks.

Nonetheless, during this energy transition, researchers, engineers, and operators face significant challenges in power distribution planning, control, and operations. The integration of renewable generators, such as wind power and photovoltaic systems, introduces intermittent characteristics that can potentially impact the efficiency and sustainability of grid operations. The intermittent nature of RES may lead to increased energy costs and pose operational challenges that need to be effectively addressed to ensure the reliable and sustainable operation of the grid [1].

Aside from that, there is also the issue of Renewable Energy Curtailment (REC). The rise of RES generators, which are dependent on uncontrollable resources, made it possible to have more RES-based energy in the grid than required to reach generation and demand balance, in some specific periods, resulting in the deliberate reduction of power output in these power plants. REC has become an increasingly important and difficult problem to

overcome regarding the planning and operation of electrical networks worldwide [2].

Different approaches have been employed in the mitigation of REC. Policies and regulations are common options, as no technical barrier is imposed [3]. Technical solutions have been established as well, demand response programs, which incentivize consumers to detach non-essential loads in times of low RES generation [4], and Energy Storage Systems (ESS) are the most widely used [5]–[7]. In electrical systems, the Pumped Hydro Storage (PHS) system is the most common energy storage technology, representing more than 90% of installed power [8], and presenting very efficient employment in the mitigation of REC [9].

Within Europe, system operators are bound by Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, which imposes certain requirements. According to this regulation, the re-dispatching of RES should be minimized and restricted to a maximum of 5% of the total annual generation. The purpose of this limitation is to mitigate potential reimbursement costs associated with re-dispatch actions. Furthermore, the regulation emphasizes the importance of non-discriminatory treatment of REC among generators, except when it is determined to be infeasible to do so. These regulatory provisions aim to ensure fair and equitable practices within the energy system while facilitating the integration of RES [10].

It is worth mentioning that two conference papers that delve into the topics and approaches of this dissertation were published:

- A. Pedroso, G. Zanatta, Â. Ferreira, et al., “An improved ga-based approach for reduced non-discriminatory renewable energy curtailment,” International Conference on Electricity Distribution, Jan. 2023, in press.
- G. Zanatta, A. Pereira, and Â. Ferreira, “On the mitigation of renewable energy curtailment by using pumped hydro storage systems,” International Conference on Modern Power Systems, Jun. 2023, in press.

1.1 Objectives

This work strives to study and analyze the use of PHS systems to mitigate REC and enhance the energy efficiency of an electrical network, through the minimization of transmission losses. In order to do so, an Optimal Power Flow (OPF) procedure was proposed to include European legislation requirements as constraints in the OPF formulation. A case study using a modified version of the standard IEEE 14-bus test feeder was conducted in order to observe the system's behavior when using a conventional generator or a PHS system.

1.2 Document Structure

This work is structured as follows:

- Chapter 1: A brief introduction and contextualization of the work are presented, as well as the main objectives and the document structure.
- Chapter 2: A literature review on renewable energy curtailment and energy storage systems is presented, highlighting important concepts and definitions.
- Chapter 3: The OPF is presented, with historical context, definitions, and formulations regarding this field of study, as well as the application in this work.
- Chapter 4: The case study carried out is described, showing the OPF procedure, the test feeder, load and generation profiles used, the PHS model, and the main objects of study.
- Chapter 5: This chapter was dedicated to showing and discussing the main results regarding the simulations of the system proposed in Chapter 4.
- Chapter 6: Finally, this final chapter pertains to the main conclusions and future lines of work.

Chapter 2

State of the Art

This chapter will present the most important concepts used in this work regarding Renewable Energy Curtailment (REC) and energy storage systems, as well as recent trends and practices in these topics. The information is divided into two sections, which present the REC and energy storage systems, respectively.

2.1 Renewable Energy Curtailment

In recent years, the penetration of Renewable Energy Sources (RES)-based power has increased worldwide. The intermittent characteristic of RES such as wind and photovoltaic has led to new challenges for operators, especially regarding the grid's planning and forecasting, as well as the system's flexibility. When there is excess energy being generated from RES, it may not always be possible to balance it, leading to REC. REC is the deliberate reduction or limitation of the output of renewable energy sources, such as wind or solar power plants, by the grid operator or energy system manager, and is perceived as a negative operation of renewable power plants, as less than the potential generation of the system is delivered to the grid [11], which could lead to economic inefficiency, for example.

Internationally, as operators have to deal with a high increase in the penetration of RES in electrical networks, the curtailment problem becomes more apparent. In 2012

and 2013, China curtailed 17.12% and 10.74% respectively, of the total wind energy that could have been generated [2]. European countries, such as Spain, even though having a high RES penetration, up to 41% in 2013 [12], had less energy curtailed, with a higher percentage being reported in 2013, of 2.14%. Market simulations indicate that wind curtailment tends to rise in the next few years [2] in northern Europe, reaching 9.3 TWh in 2030. In Europe, the increase in RES penetration has been very steep. International agreements have been pushed forward by the European Union (EU), and so regulations were proposed to accommodate such an increase. The European regulations postulate that re-dispatching must be avoided and limited. Curtailment must be based on objective, transparent, and non-discriminatory criteria, meaning that it must occur evenly among generators, using market-based mechanisms. System operators must guarantee operation with minimum possible curtailment, but that does not prevent curtailing up to 5% of the installed capacity of RES and must report to a regulatory authority, at least once per year, measures taken to reduce curtailed energy [10].

To mitigate REC, different ideas have been proposed. For example, the employment of policies, regulations, and/or financial subsidies [3], energy storage strategies, regarding different technologies such as Pumped Hydro Storage (PHS), hydrogen energy storage, electrochemical energy storage [5], [6], and demand response strategies [4], [7]. All of these strategies could effectively mitigate REC. In [13], a study is presented to demonstrate that the overloading of lines can be mitigated by using dynamic curtailment with a small quantity of curtailed energy, thus making it possible to system operators to plan the system using different approaches to the capacity. If 5% of the RES energy is curtailed, the hosting capacity of the electrical grid can be doubled. This increase in grid flexibility is regarded as a major way to mitigate REC. In standalone systems, loss of load is also a grid flexibility problem. In [14], a potential solution to address the issue of loss of load in standalone systems has been to integrate photovoltaic and PHS hybrid systems. ESS technologies were evaluated in the accommodation of RES in electrical networks. PHS systems were considered the most efficient for mitigation of curtailment, from both technical and economical perspectives [9].

2.2 Energy Storage Systems

ESS have been promising to mitigate energy curtailment scenarios at least for the last five years [15], as these systems increase the flexibility of the grid, being able to store energy when the generation rates are higher than the demand. There are multiple technologies available in the market, as well as techniques to define optimal bus siting, battery management strategies, and optimal sizing [15]. There are different technologies employed in energy storage systems, which can be classified into Mechanical, Thermal, Electrochemical, and Magnetic/ Electrical, as seen in Figure 2.1 [8], [16], [17].

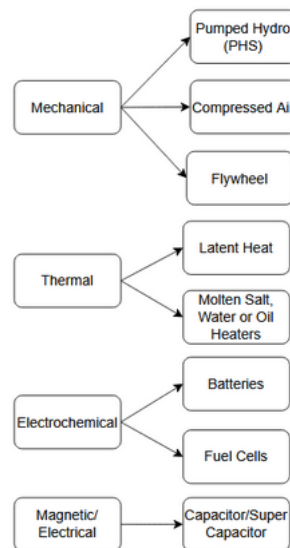


Figure 2.1: Types of energy storage technologies.

There are fundamental differences between these technologies and their applications. Some of their technical characteristics are power range, volumetric energy density, power density, and round-trip efficiency. A concise comparison of technologies regarding these technical characteristics can be found in [16]. In electrical power systems, ESS can have multiple applications, such as frequency regulation, renewable energy integration, black start services, energy shifting and capacity investment deferral, and transmission and distribution congestion relief. PHS systems are the most common, representing 92.6% of installed power as ESS, while the second most common is Electrochemical ESS, which

represents 5.2%. Li-ion Batteries account for 89% of them, as described in [8].

The basic functionality of a PHS system consists of pumping water to a reservoir when there is an energy surplus in a grid and using that water to generate electricity when the demand side is too high, as the schematic in Figure 2.2 [18] shows.

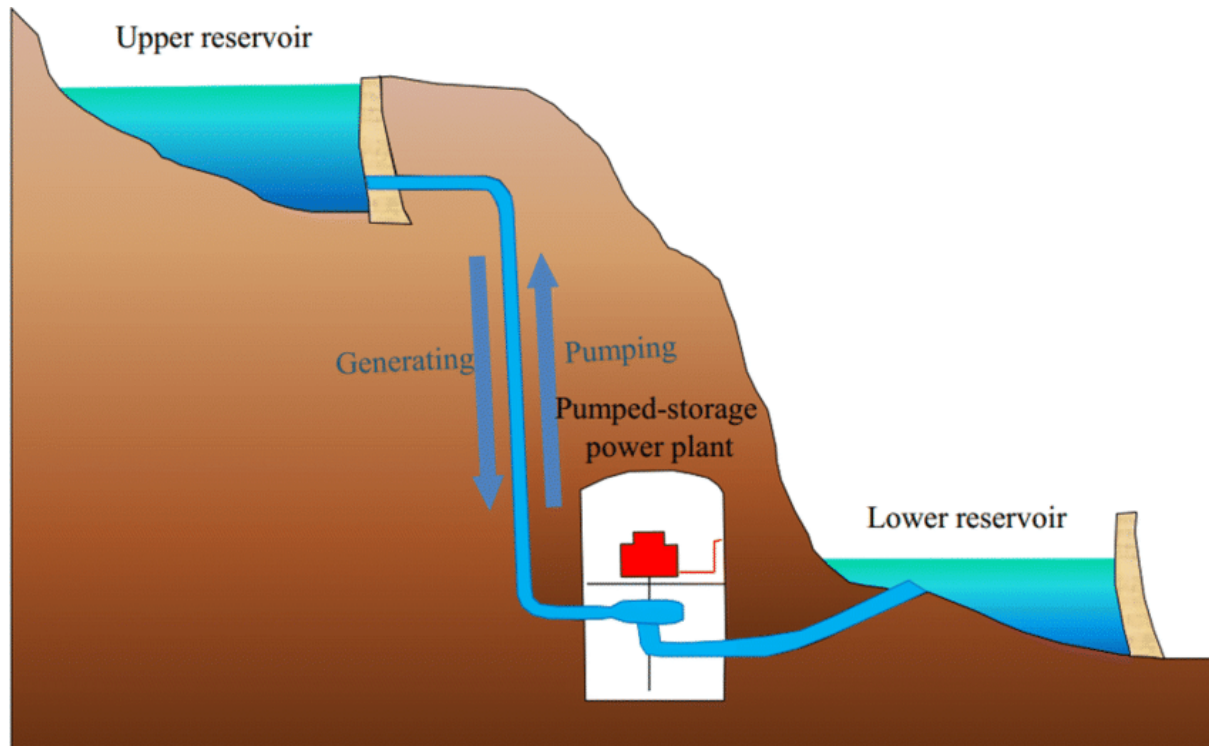


Figure 2.2: PHS schematic [18].

Since PHS presents a mature, cost-effective, long economic lifespan and very high power capacity solution it has been the go-to solution regarding the intermittent characteristic of RES [19]. The round-trip efficiency, which is the ratio of energy being stored to energy being delivered, can vary from about 70-85%, depending on reservoir capacity, the machines installed and other geographical aspects, and self-discharge can generally be negligible [20]. A way to increase the PHS system flexibility is by using multiple pumps/turbines to control pumped and generated power. For example, a seawater PHS with an installed power capacity of 1000 MW can have four 250 MW turbines [21].

There are limitations to PHS, even though it presents a very strong economic benefit when compared to other ESS, it still presents a high implementation cost and can be

restricted to geographical characteristics. In China, PHS has been a very solid solution for different problems in modern power systems, such as load shifting and improving grid reliability, as well as integrating renewable to the system [19].

Multiple algorithms have been employed in search of optimal sizing and siting of ESS, having very interesting results [8], [15]. In [15], a table with the overview of siting and sizing studies published since 2018 is presented. Different studies propose different approaches to the sizing and siting problem. The environmental, technical, social, and economic characteristics of a model are often taken into consideration, and most of these techniques optimize for one or multiple of these factors [15]. As ESS can be used to solve multiple problems in an electrical system, no single study incorporates all the nuances in the analysis.

When sizing the energy storage capacity, it is possible to quantify the storage capacity in temporal units, as shown in [14]. For instance, a PHS facility rated at 100 MW and capable of providing power for a duration of 10 hours would possess a total energy storage capacity of 1 GWh [21], [22]. In [14], the authors focus on a technical perspective and show that there is an inverse linearity between load losses, which is the inability to meet demand in a certain period, and storage capacity for isolated systems until a limit where it remains unchanged.

ESS siting algorithms can take into consideration other factors, such as overall operation cost in a power system [23], or a mix of technical and economic considerations [24]. Even though these approaches show very interesting results, some technologies, such as PHS, have their siting restricted to geographical aspects and may have more financial sense to be installed in a non-optimal bus. Another example may be battery storage systems that benefit from being installed coupled to a PV system, as the power is generated in DC, and the batteries also operate in DC. In [25] the authors showcase a real-world application of BESS with photovoltaic systems.

2.3 Chapter Considerations

This chapter highlighted some of the main themes of this study, namely renewable energy curtailment and energy storage systems. The research conducted in this chapter emphasizes the applicability of ESS to mitigate REC, particularly the most common technology employed in power systems, which is the PHS system. Under the exposed information, this work will explore the use of a PHS system to mitigate renewable energy curtailment in electrical networks.

Chapter 3

Optimal Power Flow

The Power Flow (PF) problem has garnered significant attention within the academic realm, driven by technological advancements and the escalating demand for swift and reliable calculations of electrical power systems.

This chapter exploits the historical context of power flow in the next subsection, followed by the general formulation of the power flow and optimal power flow problems. In section 3.4 the objective function and constraints are explained and classified. This is followed by an exposition of the prevailing methodologies employed to tackle the OPF problem, along with an overview of the various PF formulations. Finally, the chapter concludes by briefly presenting the challenges encountered in addressing the OPF problem and showing potential future directions for further exploration.

3.1 Historical Context of Power Flow

Efficient and reliable operation of electrical power systems has been a major issue in the past century. This problem is economical, electrical, and computational, as it requires multi-part nonlinear pricing, has non-linearities in the AC power flow formulations, and the optimization procedure has non-convexities, which makes the solvability of the problem more difficult.

During the initial half of the 20th century, the PF dilemmas remained unresolved,

requiring the reliance upon the discernment of seasoned operators and engineers. These professionals resorted to employing their expertise, and rudimentary instruments, including analog network analyzers and specialized slide rules, in order to estimate PF parameters. Later, computational tools were introduced to help these professionals. In the early 1960s [26], the first OPF problem was formulated. Linear solvers have been widely used to solve linearized versions of the problem, but the linearized versions do not translate all the nuances of the system. Non-linear solvers, on the other hand, are not deemed as robust and fast enough, and may not guarantee a global optimum. In electrical control rooms, the OPF problem may need to be solved several times in a single day [27].

Within the power systems domain, various problems are frequently investigated and discussed. This study specifically centers on power flow and optimal power flow. Power flow entails the formulation of equations that encompass generation, load, and transmission grid characteristics. Upon solving these equations, a solution is obtained, which may not necessarily be physically viable or optimal. Power flow equations may fail to consider constraints such as generator reactive power and transmission line capacities. Nonetheless, contemporary solvers often incorporate these limitations into their programming to ensure compliance with operational constraints.

Optimal power flow, on the other hand, finds an optimal solution to an objective function, which incorporates the power flow equations in the form of constraints. There are different objective functions with different constraints, and a wide variety of methods to solve this type of formulation. The formulations that use the AC form to represent the system are more difficult to solve and are called ACOPF, a linearization of this formulation has been proposed to simplify the problem and is known as DCOPF [27]. This work dwells mainly on ACOPF, but DCOPF is also briefly introduced.

3.2 General Power Flow Formulation

The power systems are solved by a model of interconnected electrical components. This model is known as the power flow model, which describes the voltages, and active and

reactive powers at each bus in the network.

This interconnection between the variables is non-linear, which means the solutions of the power flow calculations imply the solution of multiple non-linear equations, to calculate the electrical behavior of the system under given loads and generations.

In an electrical network that presents n buses, Kirchoff's law may be applied, resulting in:

$$\begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} \quad (3.1)$$

which can be represented as

$$[Y] \cdot [V] = [I] \quad (3.2)$$

where $[Y]$ is the admittance matrix, $[V]$ is the nodal voltage vector, and $[I]$ is the nodal current injection vector.

$$I_i = \frac{S_i^*}{V_i^*} = \frac{P(net)_i - jQ(net)_i}{V_i^*} \quad (3.3)$$

here, I_i is the complex injected current at bus i . S_i and V_i are the complex power and the voltage magnitude at bus i , and $P(net)_i$ and $Q(net)_i$ are respectively the active and reactive power injected at bus i , equal to the difference between active and reactive generation and loads connected to bus i .

From the equations presented, we can reach:

$$\frac{P(net)_i - jQ(net)_i}{V_i^*} = Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{in}V_n \quad i = 1, 2, \dots, n \quad (3.4)$$

which rearranged would be:

$$\frac{P(net)_i - jQ(net)_i}{V_i^*} = \sum_{j=1}^n Y_{ij}V_j \quad i = 1, 2, \dots, n \quad (3.5)$$

equating real and imaginary parts of the formulations, each bus can be defined by four variables, P , Q , $|V|$, and the voltage phase angle δ and two equations. In order to solve power flow equations, at least two variables must be specified for each bus, as to determine the others. With this in mind, the buses can be classified into three types, according to the specified and unknown variables.

Those types are:

- PV bus: Active power P and the voltage magnitude $|V|$ are known, while the reactive power Q and angle δ are unknown. A bus that has an attached generator is commonly a PV bus.
- PQ bus: Active power P and reactive power Q are known, while voltage magnitude and angle $|V|$ and δ are unknown. A consumption bus, i.e., a bus with loads, is commonly a PQ bus.
- Slack bus: The slack bus is also known as the reference bus. A generator bus is selected to be the slack bus. The power loss of the network is not known until the end of power flow calculations, and so the unknown power losses, as well as the balance of generation are assigned to this bus. It is common to have only a single slack bus in power flow calculations. The voltage of the slack bus is arbitrarily defined, which makes the voltages that need to be calculated $n - 1$, accordingly, the power flow equations number is $2(n - 1)$.

The power flow equations are nonlinear, so different methods have been proposed to solve them. The methods are iterative and usually start with a guess of the initial solution. Some of the methods are Gauss-Seidel, that has is usually used for smaller systems, decoupling, which is simpler and requires less computational power, and Newton-Raphson, which presents a fast convergence and is very accurate.

The Newton-Raphson formulation is hereby presented. The general form of a set of

non-linear equations f with n variables is:

$$\begin{cases} f_1(x_1, x_2, \dots, x_n) = 0 \\ f_2(x_1, x_2, \dots, x_n) = 0 \\ \vdots \\ f_n(x_1, x_2, \dots, x_n) = 0 \end{cases} \quad (3.6)$$

to solve this set, an arbitrary initial solution x_i^0 is selected. The difference between this value and the final solution x is Δx^0 , so

$$\begin{cases} f_1(x_1^0 + \Delta x_1^0, x_2 + \Delta x_2^0, \dots, x_n + \Delta x_n^0) = 0 \\ f_2(x_1^0 + \Delta x_1^0, x_2 + \Delta x_2^0, \dots, x_n + \Delta x_n^0) = 0 \\ \vdots \\ f_n(x_1^0 + \Delta x_1^0, x_2 + \Delta x_2^0, \dots, x_n + \Delta x_n^0) = 0 \end{cases} \quad (3.7)$$

then, applying the Taylor series expansion and ignoring the second and higher derivatives would result in the following matrix formulation

$$\begin{bmatrix} f_1(x_1^0, x_2^0, \dots, x_n^0) \\ f_2(x_1^0, x_2^0, \dots, x_n^0) \\ \vdots \\ f_n(x_1^0, x_2^0, \dots, x_n^0) \end{bmatrix} = - \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \dots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \dots & \frac{\partial f_2}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \dots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \\ \vdots \\ \Delta x_n^0 \end{bmatrix} \quad (3.8)$$

where the $\Delta X^0 = [\Delta x_1^0, \Delta x_2^0, \dots, \Delta x_n^0]^t$ vector can be obtained, which then represents a new solution. This is an approximate solution, so further iterations must be put in place.

These iterations can be expressed as:

$$\begin{bmatrix} f_1(x_1^k, x_2^k, \dots, x_n^k) \\ f_2(x_1^k, x_2^k, \dots, x_n^k) \\ \vdots \\ f_n(x_1^k, x_2^k, \dots, x_n^k) \end{bmatrix} = - \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \dots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \dots & \frac{\partial f_2}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \dots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \begin{bmatrix} \Delta x_1^k \\ \Delta x_2^k \\ \vdots \\ \Delta x_n^k \end{bmatrix} \quad (3.9)$$

and

$$x_i^k + 1 = x_i^k = \Delta x_i^k \quad i = 1, 2, \dots, n \quad (3.10)$$

the iteration can be stopped if $\max|\Delta x_i| \leq \epsilon$, where ϵ is a positive and small number, which represents the convergence precision permitted. With J being the Jacobian matrix, the presented formulation can be written in matricial form as:

$$F(X^k) = -J^k \Delta X^k \quad (3.11)$$

$$X^{k+1} = X^k + \Delta X^k \quad (3.12)$$

These mathematical principles can be applied to solve both polar coordinate systems and rectangular coordinate systems of power flow equations. Considering V_i , P_i , Q_i the complex voltage, active power and reactive power respectively at bus i , the specific polar formulations are:

$$V_i = |V_i|(\cos\delta_i + j\sin\delta_i) \quad (3.13)$$

$$P_i = V_i \sum_{j=1}^n |V_j|(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) \quad (3.14)$$

$$Q_i = V_i \sum_{j=1}^n |V_j|(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) \quad (3.15)$$

here, δ_{ij} is the voltage phase angle difference between buses i and j , i.e. $\delta_{ij} = \delta_i - \delta_j$.

In a network with n buses, the buses between 1 and m are considered PQ, buses between $m + 1$ and $n - 1$ are considered PV, and the n th bus is the slack bus. To all buses, the difference between the scheduled and produced real power, P_{sch} and P_i is represented as ΔP_i , such as:

$$\Delta P_i = P_{sch} - P_i = P_{sch} - V_i \sum_{j=1}^{n-1} |V_j|(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) \quad (3.16)$$

being G_{ij} and B_{ij} the conductance and susceptance between buses i and j respectively.

In the same way, for ΔQ_i

$$\Delta Q_i = Q_{sch} - Q_i = Q_{sch} - V_i \sum_{j=1}^m |V_j| (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \quad (3.17)$$

applying (3.11) and (3.12), we find the following equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = -J \begin{bmatrix} \Delta \delta \\ \Delta V/V \end{bmatrix} \quad (3.18)$$

or

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = - \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ V_D^{-1} \Delta V \end{bmatrix} \quad (3.19)$$

where

$$\Delta P = \begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ \vdots \\ \Delta P_{n-1} \end{bmatrix}, \quad \Delta Q = \begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_m \end{bmatrix}, \quad \Delta \delta = \begin{bmatrix} \Delta \delta_1 \\ \Delta \delta_2 \\ \vdots \\ \Delta \delta_{n-1} \end{bmatrix}, \quad \Delta V = \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_m \end{bmatrix} \quad (3.20)$$

and

$$V_D = \begin{bmatrix} V_1 & & & \\ & V_2 & & \\ & & \ddots & \\ & & & V_m \end{bmatrix} \quad (3.21)$$

where

$$\left\{ \begin{array}{l} H_{ij} = \partial \Delta P_i / \partial \delta_j \\ N_{ij} = V_j (\partial \Delta P_i / \partial V_j) \\ M_{ij} = \partial \Delta Q_i / \partial \delta_j \\ L_{ij} = V_j (\partial \Delta Q_i / \partial V_j) \end{array} \right\} \quad (3.22)$$

in this formulation, by definition, the elements where $i \neq j$ in the Jacobian matrix can

be calculated by the relations

$$\left\{ \begin{array}{l} H_{ij} = -V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \\ N_{ij} = -V_i V_j (G_{ij} \cos \delta_{ij} - B_{ij} \sin \delta_{ij}) \\ M_{ij} = V_i V_j (G_{ij} \cos \delta_{ij} - B_{ij} \sin \delta_{ij}) \\ L_{ij} = -V_i V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \end{array} \right\} \quad (3.23)$$

in the same way, elements where $i = j$ in the Jacobian matrix can be computed as

$$\left\{ \begin{array}{l} H_{ii} = V_i^2 B_{ii} + Q_i \\ N_{ii} = -V_i^2 G_{ii} - P_i \\ M_{ii} = V_i^2 G_{ii} - P_i \\ L_{ii} = V_i^2 B_{ii} - Q_i \end{array} \right\} \quad (3.24)$$

Figure 3.1 shows the flow chart with the main steps to solve the PF through the Newton-Raphson method, with the voltage expressed in the polar form [28].

In this work, the Newton-Raphson method was used to solve power the power flow calculations, for its robustness and accuracy. This method is also the standard in MATPOWER [29], a powerful free, open-source tool for electric power systems simulation and optimization, which was used to run the power system simulations.

3.3 General Optimal Power Flow Formulation

The OPF problem is formulated as:

$$\text{Min } f(x) \quad (3.25)$$

$$\text{s.t } g(x) = 0 \quad (3.26)$$

$$h(x) \leq 0 \quad (3.27)$$

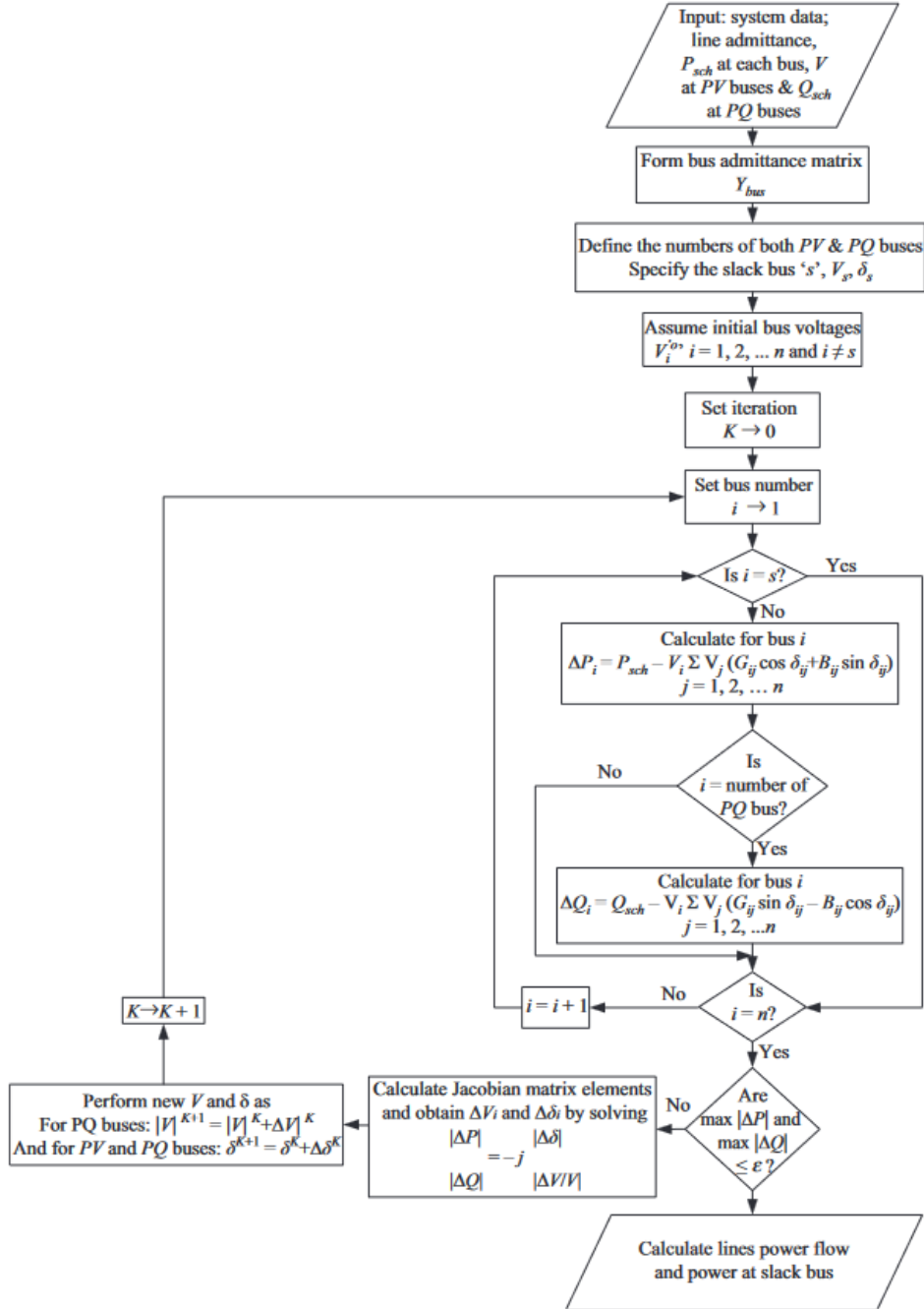


Figure 3.1: Flow chart for Newton-Raphson power flow solution with polar coordinates [28].

where $f(x)$ is the function to be minimized, $g(x)$ is the equality constraints of the problem, and $h(x)$ is the inequalities constraints. x is a vector that contains the power flow variables, presented in the preceding subsection.

The OPF problem is complex because of the non-linear equality constraints. Those constraints are imposed to generate a solution that guarantees a stable and secure functionality of the grid. The standard equality formulations are:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^n |V_j| (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) = 0 \quad (3.28)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^n |V_j| (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) = 0 \quad (3.29)$$

where P_{Gi} and Q_{Gi} are the power (active and reactive) output from sources in bus i . V_i is the voltage magnitudes in bus i , P_{Di} the load at bus i [28].

The variables of the system can be limited, which is a great advantage of using optimization methods. The limits are expressed through inequalities constraints, which often represent secure operational values for the grid. The OPF standard inequalities are:

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (3.30)$$

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (3.31)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad (3.32)$$

$$S_{ij}^{min} \leq S_{ij} \leq S_{ij}^{max} \quad (3.33)$$

here, S_{ij} is the apparent power that flows through bars i and j , and the other variables have been presented beforehand.

3.4 Objective Function and Constraints

The optimization presents equality and inequality constraints, as well as an objective function. The objective function is a mathematical formulation that aims to minimize or

maximize a variable in a system.

OPF can be applied to solve different problems regarding optimization problems in the field of power systems. The most common objective functions are the minimization of generation costs [30], network transmission losses [31] and the stabilization of voltage in the system [32]. In [33], the author presents a list of other objective functions that have been exploited, such as:

- Active/reactive power loss
- Power transfer capability
- Number of controls shifted/rescheduled
- Cost of VAR investment
- Shift of control
- Load shedding
- Environmental impact
- System loadability

Objective functions may include more than one variable to minimize, thus being multi-objective functions [34]. The variables may be competing, meaning that improving one objective will worsen the other, or complementary, meaning that improving one objective may help to improve the other. In multi-variable optimization problems, there is a set of optimal solutions, which cannot be improved in one objective without neglecting another, this set of solutions is known as the Pareto front, and represent the best possible solutions to a multi-variable optimization problem.

On the other hand, the constraints in OPF problems are used to ensure the physical and operational feasibility of the system. As mentioned earlier, there are equality and inequality constraints. The standard equality constraints refer to the power flow equations and other balance constraints. Inequality constraints represent operational limitations of

the system, that are limited by upper and lower bounds. In [33], a list of inequality constraints that have been implemented was summarized such as:

- Active/reactive power generation limits
- Demand constraints
- Bus voltage limits
- Control limits
- Transmission interface limits
- Active/reactive power reserve limits
- Spinning reserve limits
- Active/reactive power flow in a corridor
- Transient security/ stability/ contingencies
- Environmental constraints

In this work, the objective function aims at the minimization of transmission losses. Minimizing transmission losses means operating the electrical network with more efficiency, which is a reasonable and important objective. Additional constraints regarding European legislation requirements are also included and will be presented in the following chapter.

3.5 Techniques for Solving OPF

OPF is a widely studied nonlinear, non-convex, large-scale optimization problem, with many applications in power systems, such as economic dispatch, state estimation, demand response, and others [35].

In the field of OPF, there is a broad range of formulations and solution techniques available. Furthermore, the evolution of electrical networks, such as the increased integration of RES power plants into the grid, has a significant impact on OPF studies.

This situation requires optimization methods that are fast, reliable, and able to integrate operational, security, and economic considerations into the power system's operation. Despite the vast array of OPF techniques available, no single formulation or solution approach has been deemed suitable for all OPF problems to date [33].

The OPF problem has been the focus of many optimization studies, with a variety of solution methods applied to solve it. These methods can be broadly categorized into deterministic and non-deterministic approaches. Deterministic methods guarantee to find a globally optimal solution, non-deterministic methods, on the other hand, are developed for their strong global search capabilities and can efficiently explore large and complex search spaces, finding solutions that are difficult or impossible to find with deterministic methods.

Deterministic methods include gradient methods, Newton's method, the simplex method, sequential linear and quadratic programming, and interior point methods. Non-deterministic methods include ant colony optimization, artificial neural networks, bacterial foraging algorithms, chaos optimization algorithms, particle swarm optimization, simulated annealing, tabu search, and various evolutionary algorithms such as the Genetic Algorithm (GA)

In [33], [36], the authors list some desirable features of OPF solvers, such as:

- High computational speed
- Reliability of solution
- Robustness of solution
- Versatility
- Incorporation of security constraints

- Discrete modeling
- Incorporation of multiple objectives
- Incorporation of multiple time periods
- Probabilistic modeling
- Low computer storage requirements
- Simplicity

In this work, the optimization procedure is solved through a GA-hybrid approach [37]. The GA is an evolutionary method, based on the genetics field. It is a powerful method to address optimization problems, either constrained or unconstrained. In this method, a population of individuals is used, and every individual represents a possible solution. In each iteration of this method, a generation is produced, which is a set of solutions. The previous generation is selected for the procedures of the method, called crossover and mutation. In the crossover, two individuals exchange information, whereas, in the mutation, new information is introduced to an individual. The classical GA method is then combined with a derivative-free local method named Nelder-Mead, which obtains a better precision solution. This hybrid method is promising in terms of execution time and achieving a feasible solution when integrating additional constraints, namely the European regulation constraints discussed previously, and has been used for the same purpose in [38] and [39]. A similar approach was compared to other optimization procedures in the same configuration in [40], where the GA-hybrid showed better convergence speed and effectiveness to determine optimal solutions in cases where the deterministic methods were unable to converge.

3.6 Types of OPF Formulation

The OPF problem is a fundamental and challenging optimization problem in power systems. Due to its inherent non-linearity and non-convexity, the OPF problem has been

traditionally formulated as a continuous nonlinear programming problem [26]. Despite its ability to accurately represent the behavior of power systems, this approach suffers from high computational complexity and requirements.

In order to overcome these limitations, a linearization of the OPF problem has been proposed as an alternative. The linearized formulation allows the use of well-established and efficient methods for solving linear programming problems, which provide speed, reliability, and good convergence properties. The most common linearized approach for the OPF problem is the DC power flow formulation, which is fully linear and allows for a single-iteration solution.

The DCOPF formulation has been widely used in the power systems industry due to its simplicity, speed, and reliability. However, its simplification may compromise the accuracy of the solution, and in some cases, the solution obtained may not be feasible. This limitation restricts the applicability of linear programming to the OPF problem [41]. Nevertheless, linear programming techniques have been extensively employed in the power systems industry to address the OPF problem.

The modeling of control elements, including switched capacitor banks, is a crucial aspect of power system optimization. However, traditional linearization methods may not adequately capture the discrete behavior of these elements. To overcome this limitation, mixed integer linear programming has been utilized to solve linearized power system models, thereby accommodating discrete variables [33]. This technique has been used in different studies [42]–[44], but still suffers from the limitations of the linearization of the system, more specifically, the lack of accuracy and the solution being not feasible.

Mixed integer non-linear programming is then used to represent the power system with control elements in the most accurate and complex way. This formulation is the most difficult kind of optimization problem. In that sense, there is a strong relation between the complexity of a formulation and how accurately it models the system. In [45] the authors solve a mixed integer non-linear programming OPF via a hybrid particle swarm optimization.

3.7 Challenges and Future Directions

This section presented the main formulations, constraints, and an overview of OPF, as well as the specific approach explored in this work. In the last century, a lot of progress was made in this field. Nonetheless, the introduction of new constraints and decision variables is regarded as an additional challenge, and the model can be further developed to include other requirements, such as security constraints, reserve requirements, renewable policy requirements, and stability constraints, as regarded in [46]. The need to increase system flexibility and reliability in the electrical networks made that different technical characteristics of these systems should be exploited in formulations [47], [48]. With the increase of computational power available to researchers, engineers, and operators, the OPF problem has immense potential to continue to be developed.

Chapter 4

Analysis of PHS System for Curtailment Mitigation

To validate the use of PHS systems to mitigate REC under the jurisdiction of the European Union, this chapter presents the procedure for the simulations that were carried out through an OPF formulation, integrating European regulation requirements as constraints, for an exemplary day and yearly simulations, as well as other important considerations such as the PHS model and load and generation scenarios. The case study was implemented in a modified version of the IEEE 14-bus test feeder, to analyze the behavior of electrical networks under curtailment scenarios. The approach presented in this section has been validated in [39].

4.1 European Union Legislation Constraints

To integrate European legislation [10] into the OPF problem, namely the legislation requirements of curtailed energy limitation and non-discriminatory curtailment between generators, constraints were added to the OPF formulation. In this study, the curtailment is described as the percentage of energy not used relative to the total available in each generator, such as:

$$C_i = \frac{(P_i^{max} - P_i)}{P_i^{max}} \quad (4.1)$$

where C_i is the curtailed power at bus i , P_i is the vector that contains the power delivered to the grid from RES power plants, P_i^{max} is the maximum available power at each RES power plant and i is the respective bus. The European legislation [10] states that the curtailment must be limited to 5% of the annual generation for each generator, resulting in the following inequality:

$$C_i \leq 0.05 \quad (4.2)$$

the non-discriminatory characteristic is exploited via the cumulative standard deviation D of the total curtailed energy at each RES-based power plant:

$$\sqrt{\frac{1}{n} \sum_i (\sum_t (C_i(t) - \mu(t)))^2} \leq D \quad (4.3)$$

where n is the total number of nodes that have RES-based generators, i is the RES generator number, and $\mu(t)$ is the mean of active power curtailed of all the generators till the time step t .

This approach deals with discrimination as an inequality constraint in the OPF formulation. A similar approach to exploit the non-discriminatory behavior of the curtailment has been proposed in [49]. In the case study, D was limited to 5%.

4.2 Procedure for Case Study

The case study was set up in a modified version of the IEEE 14-bus test feeder, represented in Figure 4.1. The simulations presented in this work were set up using MATPOWER [29], with the objective function of minimizing transmission losses and the GA-hybrid approach to the optimization procedure, which were introduced in the preceding chapter.

The generator on bus 3 was changed into a wind power plant, and buses 6 and 8 were

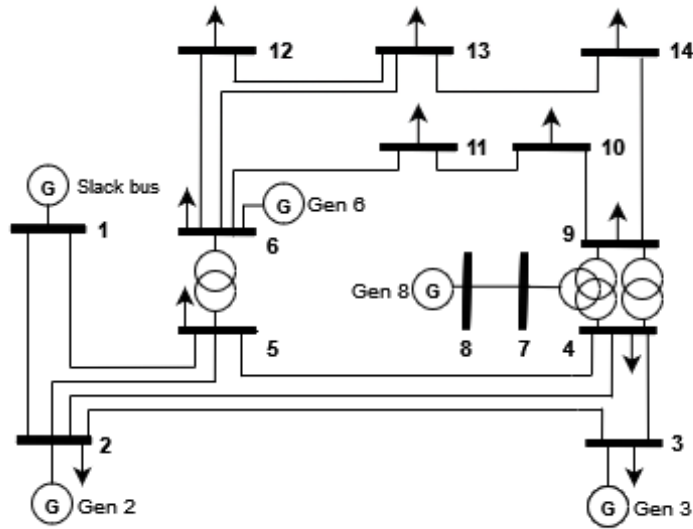


Figure 4.1: IEEE 14-bus test feeder.

changed into photovoltaic power plants. The OPF is implemented dynamically in the period T of one year over the time steps t , which are described by the load and generation profiles.

The thermal line limits were considered as 100 MVA to every branch, the limits of the magnitude of voltage were 1.05 p.u. to 0.95 p.u., the voltage phase angles were limited between -90° and $+90^\circ$, and other data was the same as the IEEE 14-bus original data presented in [50], with the base impedance of 100 MVA.

4.3 Load and Generation Profiles

To represent the annual operation of the grid, two load profiles, and four generation profiles were defined. As mentioned earlier, the generators in buses 6 and 8 are photovoltaic, and the one in bus 3 is a wind park. The power output of those technologies depends mostly on the weather. To define the generation profiles, 20 years of weather data were used from the city of Bragança, Portugal [51]. The photovoltaic power plants were defined as in winter or summer, and daily variability of the wind was considered as well, on windy and non-windy days. The former is scaled to twice the generation of the latter. Thus

resulting in four scenarios, windy summer (S1), summer (S2), windy winter (W1), and winter (W2). These scenarios were regarded as enough to represent the behavior of the electrical network in a yearly analysis.

The load profiles were obtained through a real dataset of residential and industrial loads [52]. As mentioned earlier, load profiles represent winter and summer, and winter has a higher overall energy consumption. The buses either have a completely residential profile (buses 3, 4, and 5), a completely industrial profile (buses 2, 6, and 10), or a combination of both (buses 9, 11, 12, 13, and 14). Table 4.1 summarizes the loads at each bus.

Table 4.1: Load data for proposed simulations

BUS	Load
1	NONE
2	Industrial
3	Residential
4	Residential
5	Residential
6	Industrial
7	NONE
8	NONE
9	Residential and Industrial
10	Industrial
11	Residential and Industrial
12	Residential and Industrial
13	Residential and Industrial
14	Residential and Industrial

The generation and load values were scaled to better fit the magnitude of the IEEE 14-bus standard grid. In [38] a similar approach was used. Figures 4.2, 4.3, 4.4, and 4.5 show the load and generation profiles of the whole grid for all proposed scenarios.

4.4 Pumped Hydro Storage Model and Operation

The PHS model proposed in this work has been validated in [39]. The model represents a PHS with two highly efficient reversible pump-turbine machines, which for the sake

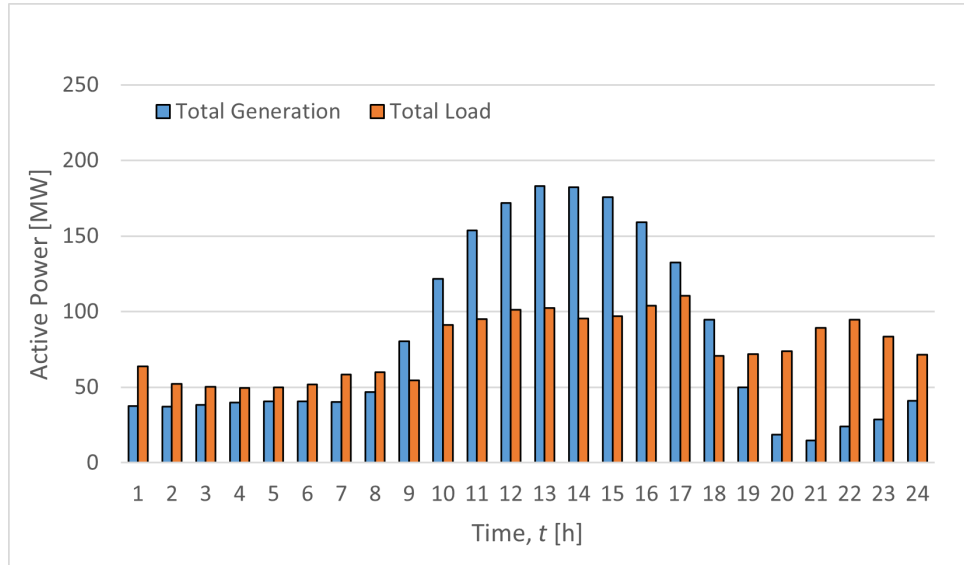


Figure 4.2: S1 load and generation profile.

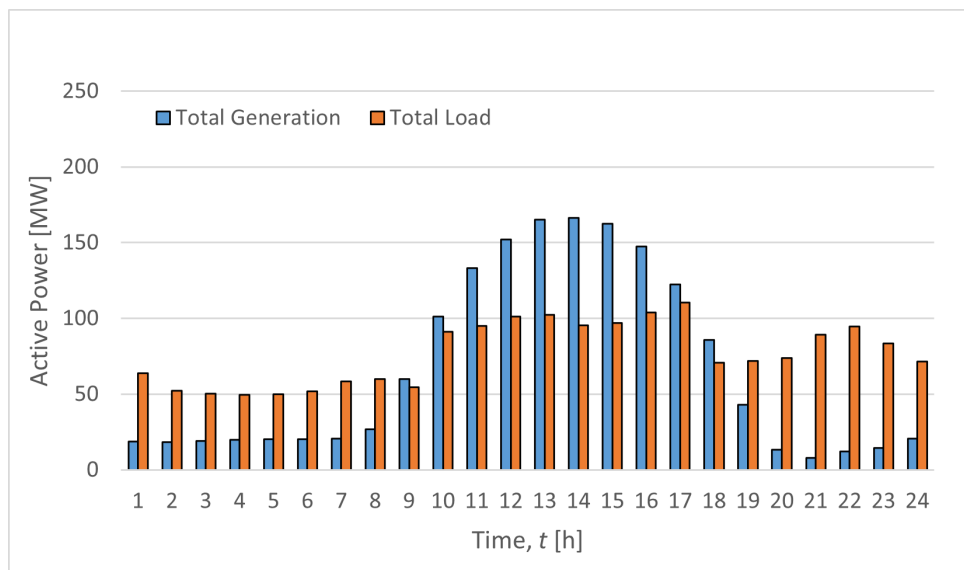


Figure 4.3: S2 load and generation profile.

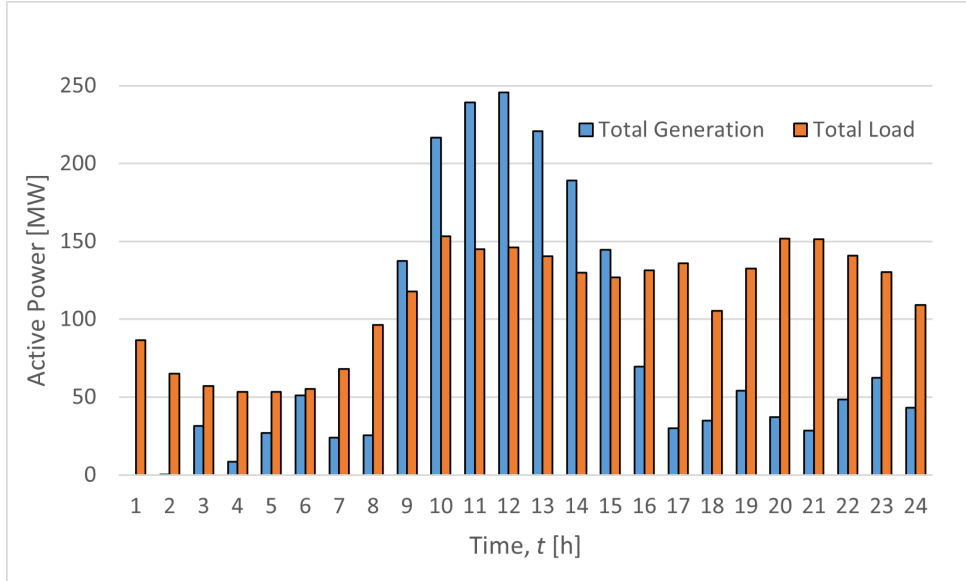


Figure 4.4: W1 load and generation profile.

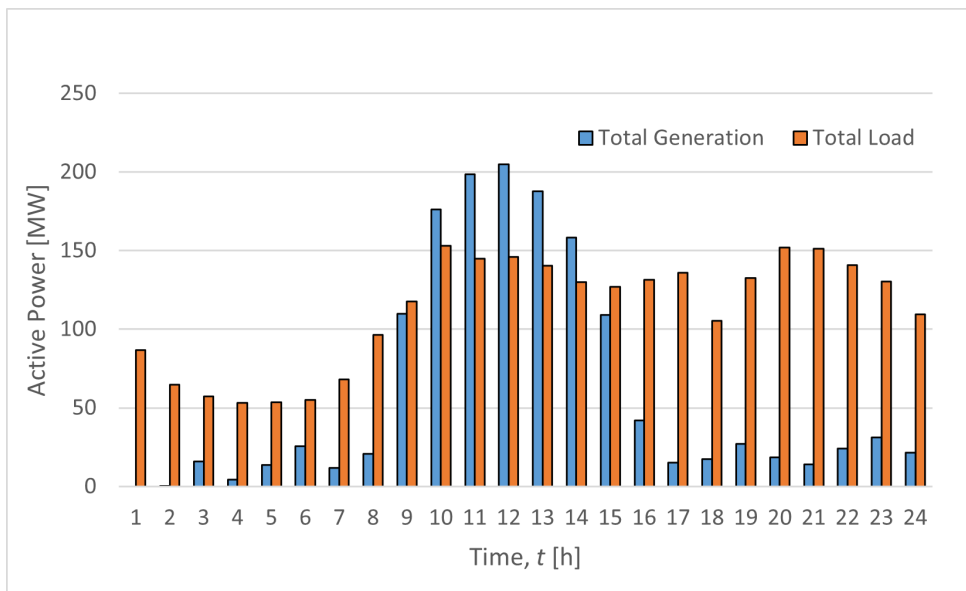


Figure 4.5: W2 load and generation profile.

of simplicity, will always operate at the rated power. The maximum and minimum energy storage capacities are not determined by the water volume of the reservoir but by the usable energy stored, as proposed in [14]. The system may operate in three states: Charging, when water is being pumped into the upper reservoir. Discharging, when the water is flowing to the lower reservoir to generate electricity, and Static when the PHS is essentially not operating.

The rated power of each turbine is 40 MW, resulting in a total of 80 MW of rated power for the PHS. The system's round-trip efficiency is considered 85%, which is very efficient, but reasonable, as suggested in different studies [16]. The total energy storage capacity is 960 MWh, which was defined under the assumption that the system could operate for 12 straight hours, as the highest possible power output of the system is 80 MW. The capacity is not affected by seasonality in this study.

The logic presented in Figure 4.6 was determined to operate the system. Objectively, the algorithm decides, for every time step t , in which of the presented states the PHS must operate, and how many machines must be turned on.

The inputs of the algorithm are the sum of loads (Total Load) and RES-based generation (Total Generation) for all the buses, as well as the PHS capacity (Capacity) at a time t . PHS capacity is checked first, to guarantee that the operation is within the capacity bounds. If the capacity is not between the maximum (MaxCapacity) and the minimum (MinCapacity), the PHS will operate in Static mode. In case the capacity is within the bounds, the algorithm will check whether the Total Generation is higher than the Total Load, if it is, the PHS will operate in Charging mode, requiring energy from the grid. If it is not, the PHS will operate in Discharging mode, delivering power to the grid.

Finally, the logic must determine how many of the machines will operate. The number of active machines results from the module of the difference between Total Load and Total Generation, divided by the total rated power of the PHS, in the presented case study, 80 MW. In case the result is higher than 50%, both machines are turned on, if it is lower than 50% but higher than 5%, only one machine will turn on, but if the result is less than 5%, no machine will operate. In that sense, the PHS system may inject or require more

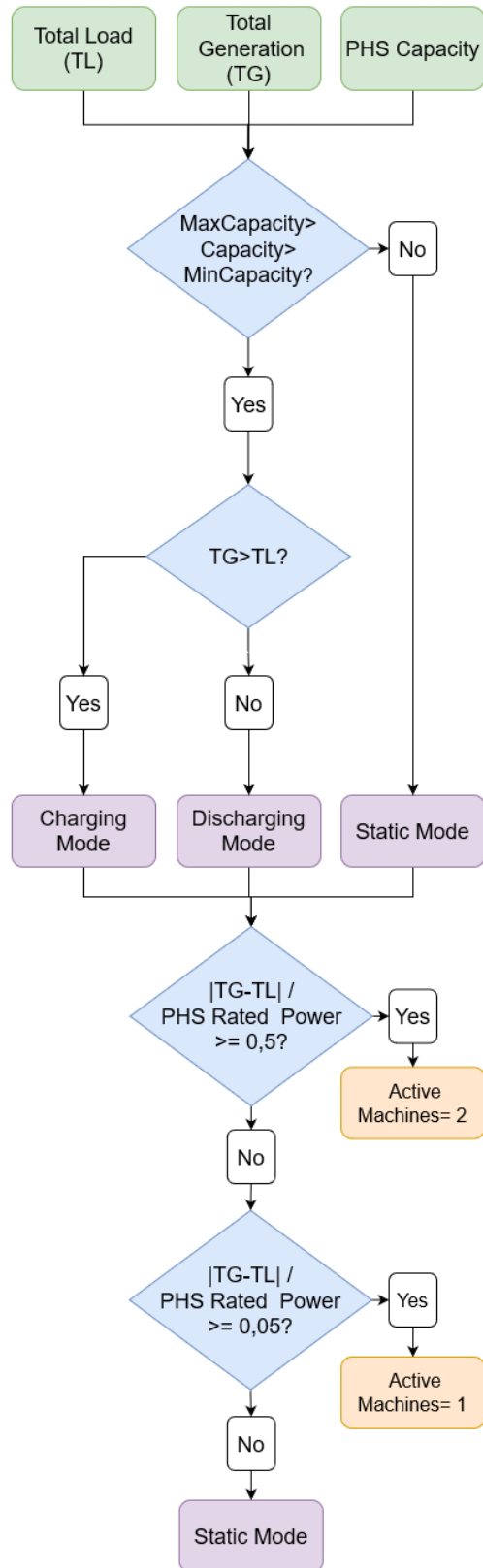


Figure 4.6: Proposed PHS operation logic.

power than optimal to balance the generations and loads.

To exemplify, at time t , assuming a load of 130 MW and renewable generation of 70 MW, the PHS system is activated to discharge while both machines are turned on. This results in a response of 80 MW, which exceeds the amount necessary to achieve equilibrium between the load and generation, meaning that this proposed logic is not optimal.

4.5 Benchmark Cases

To study the potential impacts of the proposed PHS system, two reference cases, namely Ref1 and Ref2, were employed, as well as two cases where the PHS was implemented, namely PHS1 and PHS2. All the cases employed the OPF and the equality and inequality constraints described previously.

Ref1 presents the configuration of the standard IEEE 14-bus test feeder, which incorporates a conventional generator of 40 MW of rated power attached to bus 2, which continuously injects power into the grid. The objective is to evaluate whether the PHS system offers advantages beyond increased sustainability when compared to conventional generators.

Ref2, on the other hand, modifies the standard IEEE-14 bus test feeder model by detaching the conventional generator from bus 2. This is necessary in order to examine the behavior of the slack bus, which is considered in this work to be the utility grid.

In the PHS cases, the proposed PHS system described in this section was integrated into the systems to study its effects on an electrical network operating under curtailment conditions.

The PHS1 case attached the PHS to bus 2 and detached the conventional generator from where it was originally attached.

The PHS2 case, on the other hand, attached the PHS system to bus 3 and also detached the conventional generator from where it was originally attached.

Table 4.2 summarizes the configuration of generators and the PHS system in the grid

in terms of the proposed cases.

Table 4.2: Generator data for proposed simulations

BUS	Ref1	Ref2	PHS1	PHS2
1	Utility grid	Utility grid	Utility grid	Utility grid
2	Conventional Generator	NONE	PHS	NONE
3	Wind Park	Wind Park	Wind Park	Wind Park and PHS
4	NONE	NONE	NONE	NONE
5	NONE	NONE	NONE	NONE
6	Solar Park	Solar Park	Solar Park	Solar Park
7	NONE	NONE	NONE	NONE
8	Solar Park	Solar Park	Solar Park	Solar Park
9	NONE	NONE	NONE	NONE
10	NONE	NONE	NONE	NONE
11	NONE	NONE	NONE	NONE
12	NONE	NONE	NONE	NONE
13	NONE	NONE	NONE	NONE
14	NONE	NONE	NONE	NONE

4.6 Exemplary Day and Annual Analysis

A single day was selected as a representative example to investigate the differences in the operating behavior of the electrical system in the four cases, namely Ref1, Ref2, PHS1, and PHS2.

The selected day corresponded to an exemplary day under the W1 scenario (see Figure 4.4) and was subjected to an in-depth analysis of several key parameters, including REC, transmission losses, slack bus behavior, and the PHS's capacity curve.

The other load and generation profiles presented similar results, nonetheless, for the sake of simplicity, only the W1 scenario will be further analyzed as an exemplary day in the following chapter.

A comprehensive annual simulation, considering the simulation period as a full year, with the load and generation profiles restricted to 92 days each for W1, W2, S1, and S2, was conducted for three of the cases, namely Ref1, PHS1, and PHS2.

The objective is to evaluate and contrast the energy curtailment and losses associated

with the power grid operation employing a conventional generator versus the proposed PHS system, installed in different buses.

Ref2 simulations were primarily executed to comprehend the behavior of the slack bus and ensure that the PHS would not unduly burden the public grid with power requirements, rendering a complete annual simulation unnecessary.

4.7 Case Study Summary

The case study presented in this chapter was implemented to evaluate the effects of the use of PHS systems to mitigate REC. The OPF formulation and procedure was presented in the preceding chapter, with the constraints described in this chapter representing the legislation requirements. The load and generation profiles determined to represent a whole year were then presented. A PHS model and operation was presented, and then the benchmark cases which were selected to represent the different configuration of the electrical grid, including the PHS siting.

Finally, the benchmark cases were simulated and studied under an exemplary day and under the yearly behavior of the system. The next chapter will dive into the results of mentioned simulations.

Chapter 5

Analysis of Simulation Results

The outcomes of the simulation are presented in this chapter and the following analysis seeks to highlight the most important findings, specifically regarding the behavior of the network concerning REC, transmission losses, slack bus dependence, and, for the PHS cases, the capacity curve of the system.

The winter (W1) scenario, presented in the previous section, is deeply showcased as an exemplary day. Then, the results of the annual simulation, which engulfs the four load and generation scenarios (W1, W2, S1, and S2) are presented and discussed.

5.1 Results for Winter Exemplary Day Scenario

This section examines proposed cases under the W1 generation and load profiles, which exhibit a high wind energy output on a typical winter day. The results for this exemplary day will be thoroughly analyzed, as to showcase the behavior of each case in this exemplary day.

Upon careful analysis of the W1 profile (see Figure 4.4), it is evident that the hours between 9 and 15 may experience a significant amount of curtailed energy, given that the RES generation significantly surpasses the load demands during this period. In light of this, an investigation was conducted for the Ref1, Ref2, PHS1, and PHS2 cases, previously presented.

5.1.1 Energy Curtailment

Curtailed energy in the RES generators is a very important metric to analyze. Figure 5.1 shows the sum of curtailed energy of each of the RES-based generators, for all the investigated cases in the W1 exemplary day.

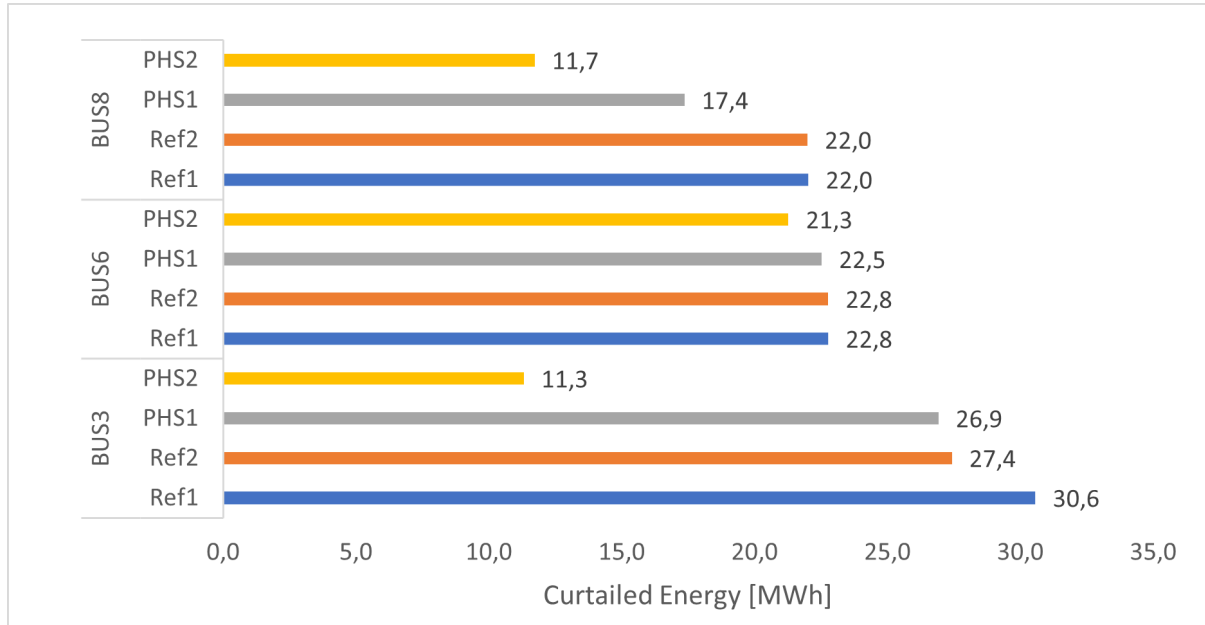


Figure 5.1: Curtailed energy comparison for W1.

The study's results demonstrate that both the cases which implemented the PHS system, namely PHS1, and PHS2, resulted in a reduction of curtailed energy for all generators in the W1 scenario when compared to both references. Ref2 yields nearly the same curtailed energy output as Ref1, except in bus 3.

Notably, Ref1 generates the highest curtailed energy for all RES-based generators, which can be attributed to the conventional generator connected to Bus 2, along with the objective function aimed at minimizing transmission losses. The operation of the conventional generator may undermine the power output of RES generators.

To gain a clearer understanding of the periods during which RES power plants were curtailed, a curtailed power curve was generated for the cases, as illustrated in Figure 5.2.

The presented curve highlights most of the curtailment happening in hours 9 to 15, which corroborates the observations made earlier, as those are the hours when RES-based

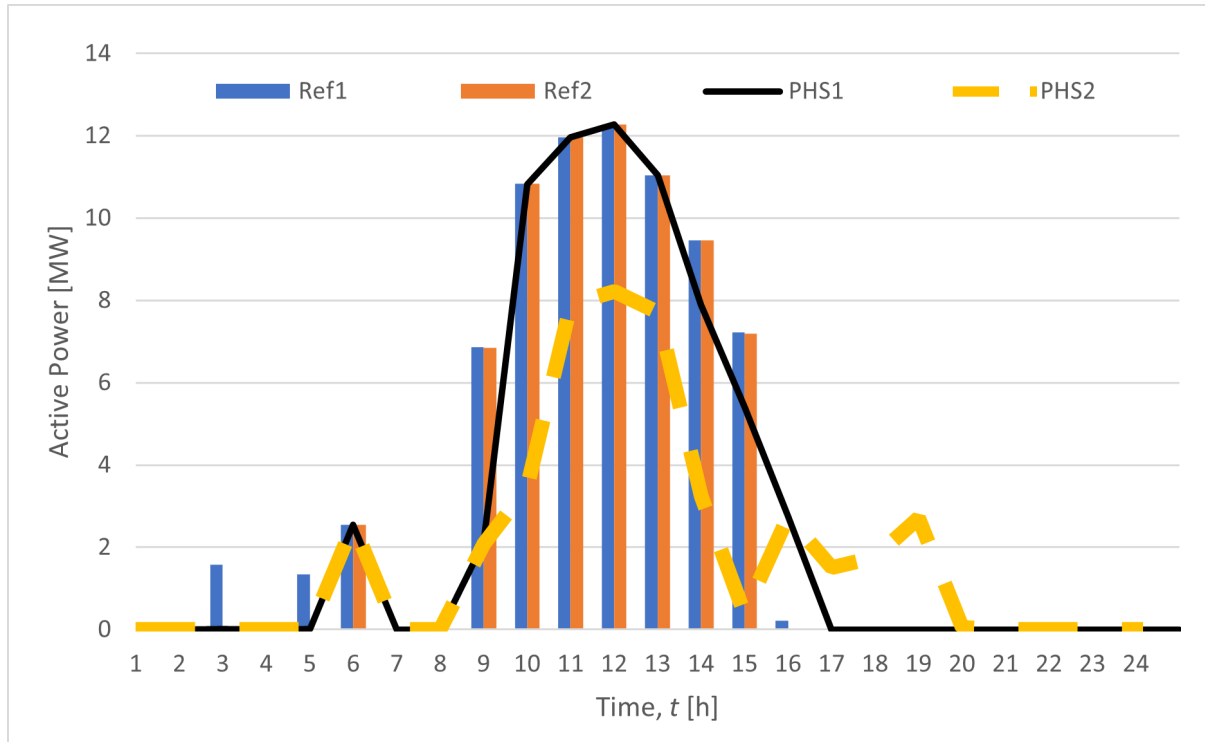


Figure 5.2: Curtailed power comparison for W1.

generation is higher than the total load of the system. A notable finding is that in specific periods, Ref1, Ref2, PHS1, and PHS2 cases exhibit identical levels of curtailed power. The PHS2 curve shows a more distinct behavior than the other cases, which suggests that attaching a storage system in the same bus as RES-based generators may cause a more constant curtailment.

5.1.2 Transmission Losses

The transmission losses are an incredibly important aspect of grid operation, even more in this work, as it is the variable to be minimized by the OPF formulation. In that sense, table 5.1 exposes the transmission losses of the cases under investigation.

Table 5.1 displays the results of the simulations, indicating that the PHS2 case yielded the lowest transmission losses for the W1 scenario, followed by PHS1, Ref1, and then Ref2, which demonstrated the highest losses.

Removing the conventional generator from the grid compelled the slack bus to supply

Table 5.1: Transmission losses comparison for W1

Case	Transmission Losses [MWh]
Ref1	30.83
Ref2	33.23
PHS1	27.82
PHS2	26.89

the requisite power, thereby elevating losses in Ref2 when compared to Ref1. With the difference in losses observed between Ref1 and the PHS1 and PHS2 cases, it is crucial to recall that the PHS system integrates higher flexibility into the system, meaning that its operational characteristics result in a greater balance of load and generation, thus decreasing transmission losses.

As to the difference between PHS1 and PHS2, even though it is relatively low, this result suggests that integrating the PHS system in the same bus as a RES-based generator may improve overall grid efficiency, in terms of transmission losses.

5.1.3 Utility Grid Dependence

In order to ascertain that the utilization of the PHS system does not create excessive dependence on the public grid, an investigation was carried out to analyze the behavior of the slack bus. Figure 5.3 illustrates the power exchange at the slack bus for the W1 scenario and Figure 5.4 summarizes of the total curtailed energy for the four proposed cases.

A comparison between the Ref1 and Ref2 curves reveals that the conventional generator minimizes the power requirement from the grid, during periods of high curtailment there is a reverse power flow at the slack bus for both cases.

The Ref1 and Ref2 curves exhibit a striking resemblance, with a constant offset of approximately 40 MW observed throughout the day. This value corresponds precisely to the power output generated by the conventional generator in Ref1. This is a crucial finding, as simply analyzing the sum of curtailed energy in Figure 5.4 could lead to erroneous conclusions that the PHS1 and PHS2 cases require excessive energy from the

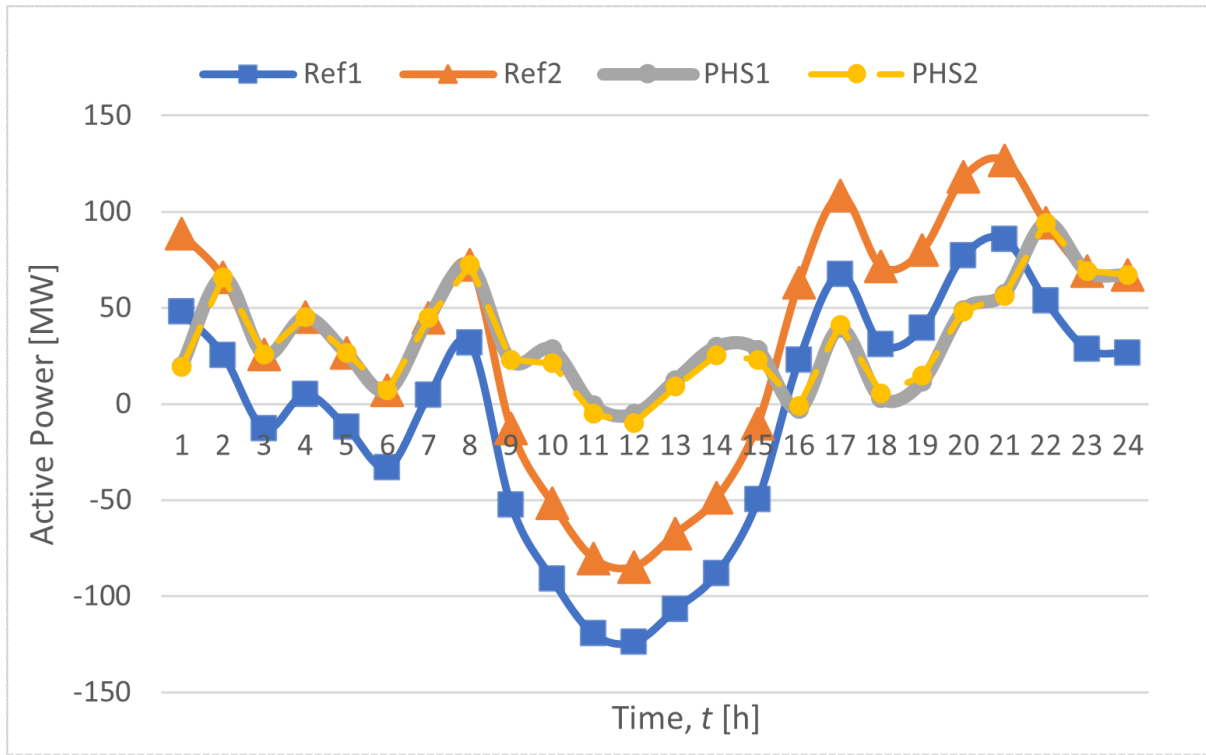


Figure 5.3: Slack bus power curve for W1.

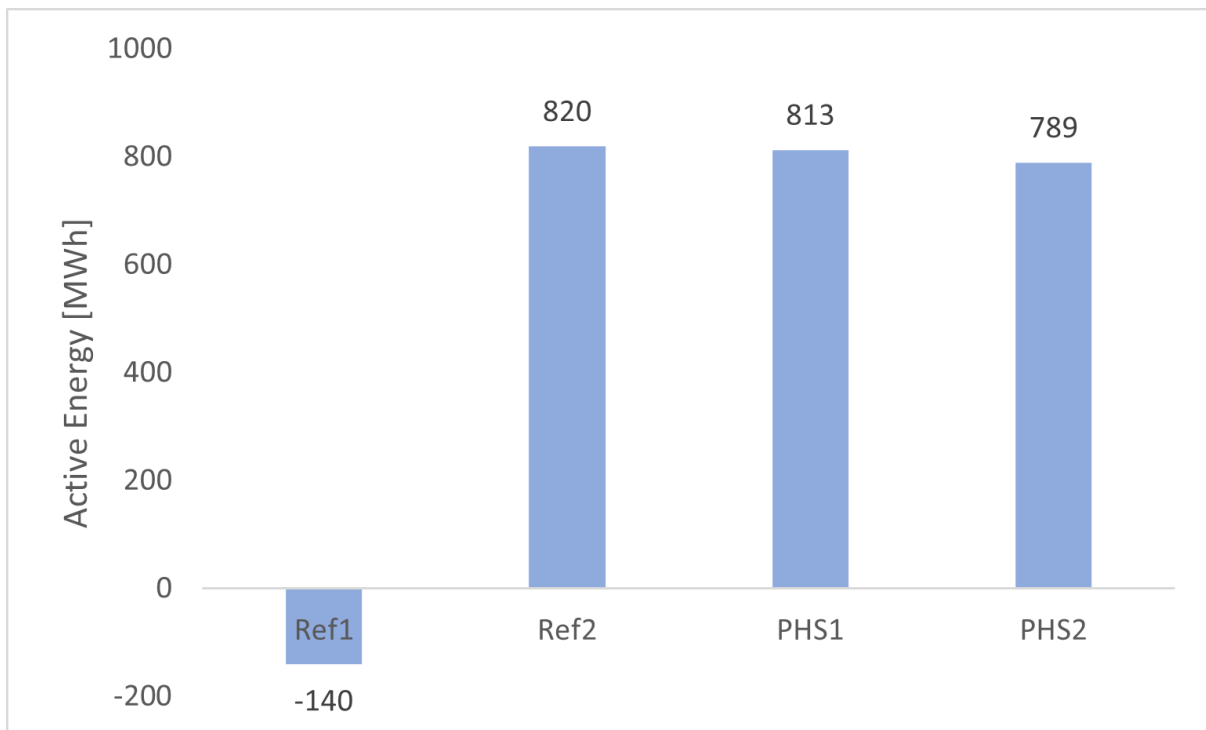


Figure 5.4: Sum of slack bus energy for W1.

slack bus to pump water, which is inaccurate, as showed before, REC is significantly reduced for the PHS1 and PHS2 cases under the W1 scenario.

Both the PHS cases, namely PHS1 and PHS2, require more energy from the slack bus than the Ref1 case. However, as noted earlier, the primary comparison should be between the PHS cases and Ref2. In this regard, a decrease is observed for the PHS cases, albeit too insignificant to impact yearly simulations.

5.1.4 Pumped Hydro Storage System Capacity

Figure 5.5 shows the capacity curve for the PHS1 and PHS2 cases on the W1 exemplary day. On this exemplary day, the initial condition for the PHS was arbitrary. However, it is essential to note that different load and generation profiles would impose different operations on the system. It is worth mentioning that the rated power of the system limits the pumping and generation rates, which in turn limits the amount of power exchanged with the grid.

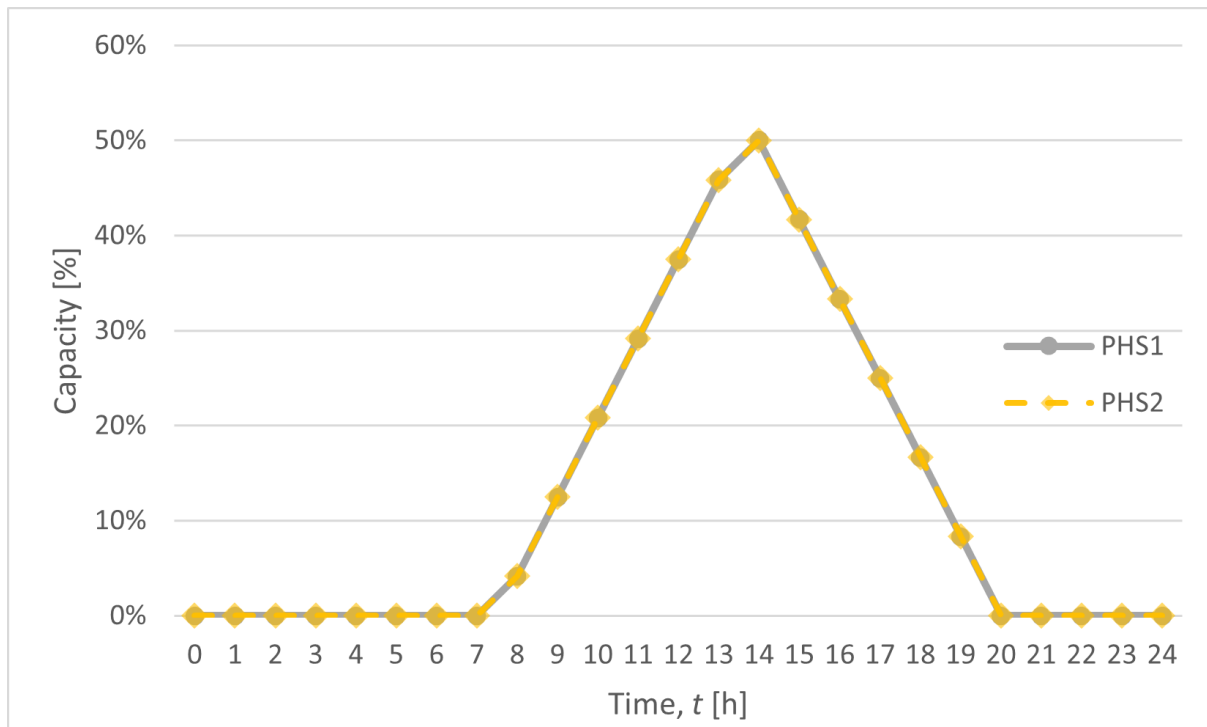


Figure 5.5: Capacity of PHS for W1.

The capacity of the PHS system may be oversized, as for both the PHS cases under the W1 scenario exemplary day it roughly reaches 50% of the total capacity. This decision was made as a way to increase the system's flexibility; nevertheless, future works may look into optimal sizing of storage systems for electrical networks under curtailment scenarios.

It is important to note that for both of the PHS cases, the PHS system behaved exactly the same. This occurs because the operation logic does not take the system's siting into consideration.

5.2 Annual Results

The annual system's performance was studied based on simulations of three cases, Ref1, PHS1, and PHS2. As mentioned in the case study chapter, the year is considered as 92 straight days of each scenario (W1, W2, S1, and S2).

It should be noted that the initial and final states of the PHS capacity were the same for each scenario in the annual simulation, as a single transition day of the load and generation profile would guarantee such behavior. Nevertheless, the system may behave differently, as shown in Figure 5.6, where arbitrary initial states were implemented to demonstrate the system's operation for the PHS1 case under these conditions.

The Ref1 case employed a standard IEEE 14-bus test feeder with a conventional generator connected to bus 2, while the PHS1 case replaced the conventional generator with the proposed PHS at bus 2, and the PHS2 case detached the conventional generator from bus 2 and attached the PHS system to bus 3. Ref2, which served primarily to ensure that the integration of PHS did not result in a higher reliance on the public grid, was not utilized in the year-long simulations. The annual simulations aim to understand better the behavior of the grid regarding:

- Curtailed energy
- Transmission losses
- Compliance to curtailment limits

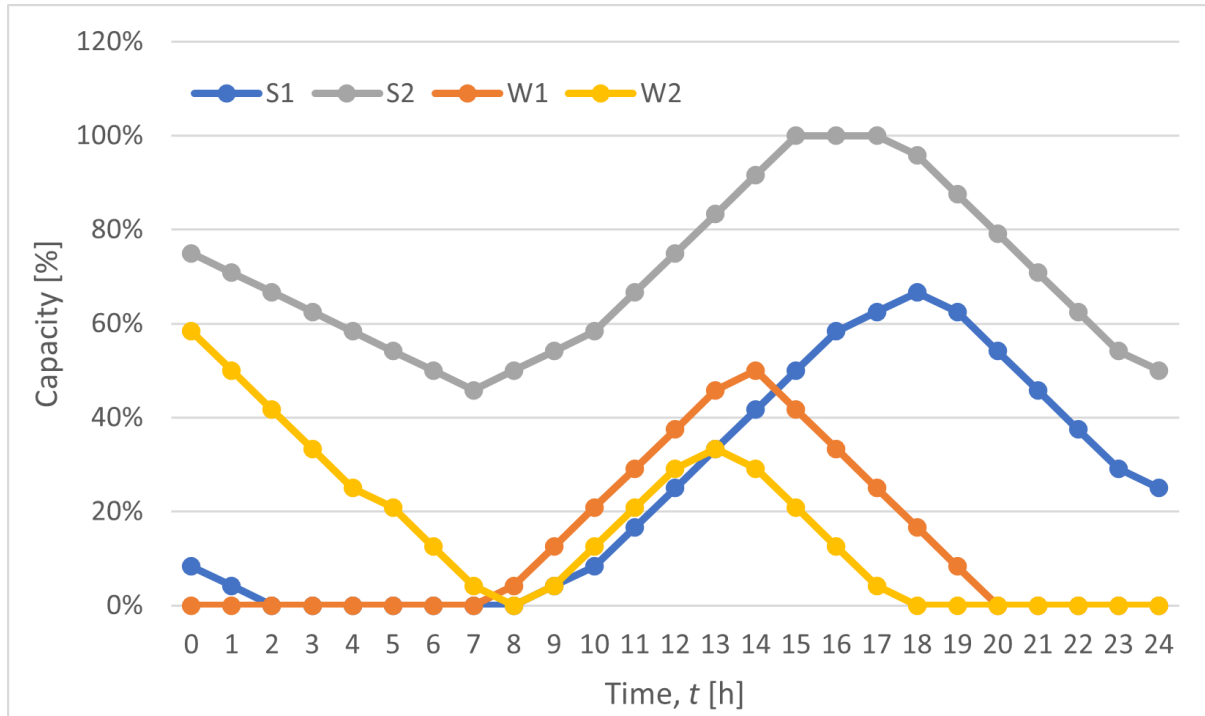


Figure 5.6: Capacity of PHS in PHS1 case for different scenarios.

- Compliance to non-discriminatory behavior between generators

5.2.1 Curtailed Energy

The main objective of this study is to understand the impacts of the PHS system in curtailment scenarios, primarily the effectiveness of mitigating REC. In table 5.2, the results of the annual simulation for Ref1, PHS1, and PHS2 cases regarding REC are presented.

Table 5.2: Curtailment results for annual scenario

Case	Total Annual Load [MWh]	Active energy curtailed [MWh]	Active energy curtailed [%]
Ref1	833119	26972	3.237
PHS1	833119	22436	2.693
PHS2	833119	17277	2.074

The findings support the hypothesis that the use of PHS systems can effectively mitigate REC. A comparison of the PHS1 and Ref1 scenarios indicates a reduction of 16.82%

in REC in the PHS1 case. On the other hand, a comparison between PHS2 and Ref1 indicates a reduction of 35.95%. By minimizing REC, the PHS system contributes to a more efficient and sustainable energy system. The actual energy saved by mitigating curtailment corresponds to approximately 4536 MWh for PHS1 and 9695 MWh for PHS2. The difference in curtailed energy observed between cases PHS1 and PHS2 supports the idea that having ESS attached to RES-based generators may be an interesting approach.

5.2.2 Transmission Losses

Reducing transmission losses is crucial for improving the reliability and efficiency of an electrical system. Minimizing the transmission losses is the objective of the OPF formulation in this research. Table 5.3 outlines the power loss results for the whole-year simulation.

Table 5.3: Transmission losses results for annual scenario

Case	Total Annual Load [MWh]	Total transmission losses [MWh]	Total transmission losses [%]
Ref1	833119	9394	1.128
PHS1	833119	9187	1.103
PHS2	833119	11122	1.335

The data presented in table 5.3 shows remarkable similarity regarding power losses between Ref1 and PHS1 cases. Comparing these cases we see a small decrease in losses for the PHS1 case, roughly 2.2%, or 207 MWh. This is a minimal difference, nonetheless, shows an improvement in the PHS1 case. As for the PHS2 case, there is an increase of 15.53% or 1728 MWh when compared to Ref1. This is an interesting result, as even though the PHS2 case presented the least curtailed energy for whole-year analysis, it also had the highest transmission losses among all the cases.

5.2.3 Curtailment Limits

The European Regulation curtailment limits and non-discriminatory behavior requirements are included in the objective function as boundary constraints, as exposed in the

case study section. One of the requirements is to curtail less than 5% of RES-based energy for a whole year.

Table 5.4 exposes the total possible energy generation and active curtailment for the Ref1 case. The PHS1 case results are presented in Table 5.5. The PHS2 case results are presented in Table 5.6. Figure 5.7 exposes the difference between curtailed energy for all generators in both cases.

Table 5.4: Curtailment comparison for Ref1

Analyzed Bus	Total RES generation [MWh]	Active energy curtailed Ref1 [MWh]	Active energy curtailed Ref1 [%]
BUS 3	249234	8254	3.312
BUS 6	188515	9219	4.891
BUS 8	200951	9497	4.727

Table 5.5: Curtailment comparison for PHS1

Analyzed Bus	Total RES generation [MWh]	Active energy curtailed PHS1 [MWh]	Active energy curtailed PHS1 [%]
BUS 3	249234	5833	2.341
BUS 6	188515	8994	4.771
BUS 8	200951	7607	3.786

Table 5.6: Curtailment comparison for PHS2

Analyzed Bus	Total RES generation [MWh]	Active energy curtailed PHS2 [MWh]	Active energy curtailed PHS2 [%]
BUS 3	249234	4378	1.757
BUS 6	188515	8849	4.694
BUS 8	200951	4050	2.015

Based on the presented results, it is evident that the three cases comply with the restriction of REC, as none of the generators had 5% or more curtailed energy. Notably, bus 6 witnessed the most significant percentage of curtailed energy, while Bus 3 experienced the least for every case.

In the PHS1 and PHS2 cases, the curtailed energy was reduced for each generator, when compared to the Ref1 case, a noteworthy observation demonstrated in Figure 5.7.

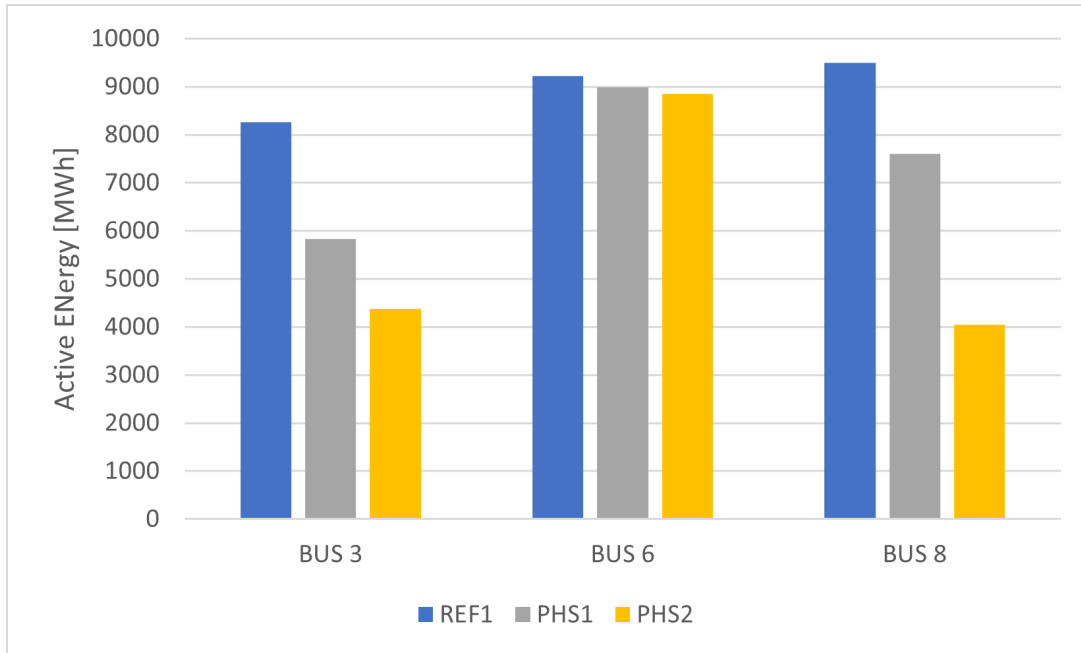


Figure 5.7: Annual curtailed energy for buses 3, 6, and 8.

Even though bus 6 had very similar curtailment ratios, this is indicative of the advantages that every energy producer gained from integrating the PHS system into the grid.

5.2.4 Discriminatory curtailment

Operators are responsible for ensuring that curtailment is non-discriminatory between generators. This work limits the standard deviation between buses to 5% of the percentage of active energy curtailment. Table 5.7 presents the percentage of curtailed energy for both scenarios, along with the value of the standard deviation D .

Table 5.7: Curtailed energy and discriminatory behavior

Case	Bus 3 [%]	Bus 6 [%]	Bus 8 [%]	D [%]
Ref1	3.312	4.891	4.727	0.87
PHS1	2.341	4.771	3.786	1.22
PHS2	1.757	4.694	2.015	1.63

A notable observation is that the three cases conform to the discriminatory limitation imposed by the constraint, in this case, 5%. In Ref1, the curtailment between generators

is comparatively more similar than in the PHS1 and PHS2 cases. The PHS2 displayed the most discriminatory behavior of all the cases, with D being 1.63%. This characteristic of the system may be attributed to the installation of the PHS system in bus 3, which is the bus that presented the lowest curtailment rate in the PHS2 case.

Although this could potentially be problematic, it is essential to recognize that all the cases studied comply with the requirement to a significant degree. This characteristic of the system could be attributed to the dynamic application of curtailed energy constraints throughout the simulation.

In order to further investigate the behavior of the grid regarding the discrimination constraint, the whole year was simulated again for the PHS1 and PHS2 cases, setting $D=1\%$.

Table 5.8 shows the results of these simulations regarding energy curtailment, showing that system could comply with the more rigorous approach. Other important parameters, namely total curtailed energy and total transmission losses are presented in tables 5.9 and 5.10.

Table 5.8: Curtailed energy and discriminatory behavior for $D=1\%$

Case	Bus 3 [%]	Bus 6 [%]	Bus 8 [%]	D [%]
PHS1	2.496	4.416	3.718	0.97
PHS2	2.207	3.930	2.391	0.95

Table 5.9: Total curtailed energy and transmission losses comparison for PHS1

Scenario	Total Curtailed Energy	Total Transmission Losses	Total Energy
PHS1 $D=5\%$	22436	9187	31624
PHS1 $D=1\%$	22018	10606	32625

Table 5.10: Total curtailed energy and transmission losses comparison for PHS2

Scenario	Total Curtailed Energy	Total Transmission Losses	Total Energy
PHS2 $D=5\%$	17277	11122	28399
PHS2 $D=1\%$	17714	12634	30348

The presented results show that even though the more rigorous approach could be implemented, the difference in total lost energy in the system was higher when $D=1\%$ in

both cases. These results show that a harsh non-discriminatory behavior requisite may lead to a less efficient operation of the system.

Chapter 6

Conclusion and Future Work

The main objective of the investigation presented in this research is to analyze the impacts of using a pumped hydro storage system to mitigate active power curtailment in electrical networks with high penetration of renewable energy sources, applying European Union regulation requirements as constraints in an optimal power flow formulation.

Through this hypothesis, the study demonstrates the potential to reduce renewable energy curtailment, thereby enhancing the efficiency and sustainability of the electrical network. A case study was conducted using a modified version of the IEEE 14-bus test feeder, incorporating renewable generators with intermittent behavior, utilizing real data from Portugal, and load data from the literature.

An analysis was carried out to understand better the proposed PHS's effects in a single exemplary day and for the whole year under the curtailment scenarios, and the OPF formulation was solved using a genetic hybrid algorithm to ensure the feasibility of the problem.

The results of the analysis indicate that the proposed PHS model could mitigate REC and transmission losses and comply with the constraints set forth by European regulations. In the single-day simulations, curtailed energy, transmission losses, slack bus behavior, and the proposed PHS capacity curve were deeply analyzed.

The main results show a decrease in REC in the cases where the PHS system was integrated, of up to 35.95% in comparison to the standard system with a conventional

generator, for a yearly operation. Transmission losses were mitigated to up to 2.21% in one of the cases.

An analysis of the non-discriminatory behavior was also carried out, as to further understand the impacts of a more rigid approach to the value of the standard deviation between generators. Simulations suggest that this strictness may lead to less efficient operation of the system.

This study successfully implemented and analyzed the impacts of using PHS systems to mitigate REC, demonstrating that this might be a suitable solution to the REC problem.

Further refinements to the PHS system are possible through various means. Overall, the results presented in this study endorse the use of PHS as an effective strategy to mitigate the curtailment of renewable energy, thereby contributing towards a more sustainable and reliable electrical network.

6.1 Future Work

This section contains suggestions on future lines of research related to the presented work, intending to further investigate the proposed solutions.

- Refinement of the proposed PHS system.
- Implementation of an optimal operation of the proposed PHS system.
- Integration of multi-variable objective function that aimed to minimize curtailed active power and transmission losses.
- Investigation and implementation of other grid flexibility strategies, such as demand response.
- Further studies of the proposed methodology in other test feeders, to better validate the approach.
- Implementation of a different solver for the optimal power flow formulation, namely particle swarm optimization.

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