Carl von Ossietzky Universität Oldenburg

Institute of Physics

Postgraduate Programme Renewable Energy

Master's Thesis

Title:

Modeling line outages and transmission line expansion in REMix-MISO

Presented by: Angela María Gamba Cárdenas

First examiner: Dr. Thomas Vogt

Second examiner: Prof Dr. Carsten Agert

Supervisors: Dr. Karl-Kiên Cao

Shima Sasanpour

Place, Date: *Germany, December 8, 2021*

Declaration

I hereby confirm that this thesis is entirely my own work. I confirm that no part of the document has been copied from either a book or any other source – including the internet – except where such sections are clearly shown as quotations and the sources have been correctly identified within the text or in the list of references. Moreover, I confirm that I have taken notice of the 'Leitlinien guter wissenschaftlicher Praxis' of the University of Oldenburg.

Mannheim, December 8th, 2021

Angela María Gamba Cárdenas

Abstract

The growing share of renewable generation results in higher power imbalances in the energy system and more situations in which transmission lines are loaded close to their thermal limits. Therefore, the aspect of the security of supply and grid expansions gain significance. This thesis presents the modeling of the impact of transmission line outages on the network power flows, the implementation of mixed-integer linear programming (MILP) transmission expansion planning (TEP), and the development of a security-constrained line expansion method that considers critical outages in TEP (SC-TEP).

A post-contingency critical lines (PCL) algorithm is developed based on the Line Outage Distribution Factors (LODF) to identify the critical lines, which cause the largest number of overloaded lines in the power system with their disconnection. The PCL algorithm is applied to the IEEE 24-bus system. The integrated method first calculates a relaxed version of TEP without security constraints to select the critical lines and then integrates the critical contingencies into the TEP. The MILP-TEP and the integrated SC-TEP method are applied to a modified version of the IEEE 24-bus system. The methods are implemented in the energy system optimization model REMix-MISO and validated with a reference model.

Overall, the optimization results show the accuracy and efficiency of the PCL algorithm, the MILP TEP, and the security-constrained line expansion method. The consideration of critical lines only in TEP can result in some critical lines not being expanded. However, the numerical results demonstrate that the integrated SC-TEP method is much faster than the application of the full N-1 criterion in MILP-TEP. Therefore, the proposed method can be used as an accelerated approximation of a N-1-secure energy system.

Acknowledgments

I wish to express my sincere gratitude to my supervisors, Karl-Kiên Cao and Shima Sasanpour, for their helpful feedback and the opportunity of developing such an interesting project. Without their support and guidance, my experience would not have been as enriching as it was.

I would like to thank all my colleagues of Energy System Modelling at the DLR for helping me with all the technical issues and for their insightful comments.

I would also like to express my gratitude towards the DAAD for the financial support during my master studies and to the PPRE team for the kind help and invaluable lessons.

Finally, special thanks go to my family and my boyfriend Jimmy for the endless patience, care, love, and encouragement when it was most needed. I would also like to thank my friends for their company and valuable advice.

Contents

List of Figures

List of Tables

Abbreviations

AC	Alternative Current
ACOPF	AC Optimal Power Flow
CHP	Combined heat and power plant
DCOPF	DC Optimal Power Flow
IEEE	Institute of Electrical and Electronics Engineers
LODF	Line Outage Distribution Factors
LOPF	Linear Optimal Power Flow
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
MISO	Modeling framework for Integrated energy System Optimization
NLP	Nonlinear programming
OPF	Optimal power flow
PCL	Post-contingency critical lines
RTS	Reliability Test System
REMix	Renewable energy mix for a sustainable power supply
SC-TEP	Security-constrained transmission expansion planning
TEP	Transmission expansion planning

Nomenclature

Indices and Sets

g	Index of thermal generating units
i, j	Index of network buses
Ω_G	Set of all thermal generating units
Ω_G^i	Set of all thermal generating units connected to bus *i*
Ω_B	Set of network buses
Ω_l^i	Set of all buses connected to bus *i*
Ω_l	Set of network branches
k	Index for a line k that could be constructed
n, m	Index of network buses connecting the line nm on outage
N_0	Set of all transmission lines for the base case before expansion
S_0	Set of all generators, transmission lines, buses and loads forming the case system before expansion
N_1	Set of transmission lines for the base case and selected candidate lines after solving the TEP problem without security constraints
S_1	Set of all generators, transmission lines, buses and loads forming the updated system after solving the TEP problem without security constraints
c	Index of the contingency states corresponding to the columns of the matrix of contingencies

Parameters and variables

P_{ij}	Active power flow of branch connecting bus *i* to *j*
P_g	Active power generated by generator *g*
L_i	Electric power demand in bus *i*
c_g	Fuel cost coefficient of thermal unit *g*
$P_g^{max/min}$	Maximum/minimum limits of power generation of generator *g*
P_{ij}^{max}	Maximum power flow limits of branch connecting bus *i* to *j*
x_{ij}	Reactance of branch connecting bus *i* to *j*
OF	Total operating costs
δ_i	Voltage angle in bus *i*
d_{ij}	Length of the branch connecting bus *i* to *j*

$x_{d_{ij}}$	Reactance per distance of branch connecting bus *i* to *j*
$x_{ij\ pu}$	Reactance in per unit of branch connecting bus *i* to *j*
U_{base}	Voltage base [kV]
S_{base}	Apparent power base [kVA]
f_{ij}^{C}	Post-outage power flow on line ij
f_{ij}^{0}	Pre-outage power flow on line ij
f_{nm}^{0}	Pre-outage power flow on line nm
$LODF_{ij,nm}$	Line Outage Distribution Factor corresponding to the impact of an outage on line nm on the power flow of line ij
B	Matrix of susceptance
$\boldsymbol{F}_{ij}^{C}$	Matrix with the post-outage power flows
$\boldsymbol{F}_{ij}^{0}$	Matrix with the pre-outage power flows
$\boldsymbol{LODF}_{ij,nm}$	Matrix of Line Outage Distribution Factors corresponding to the impact of an outage on line nm on the power flow of line ij
$\boldsymbol{P}_{ij}^{max}$	Matrix of maximum power flow limits
$\boldsymbol{CC_{ij,nm}}$	Matrix of critical cases for an outage on line nm on the power flow of line ij
CL_{nm}	List of critical lines connecting bus n to m, where an outage affects critically the network
CL_{T}	List of the most critical lines connecting bus n to m, where an outage affects critically the network
B_{ij}	Susceptance of the branch connecting bus i to *j*
α_{ij}^{k}	Binary decision variable to model the investment decision regarding the line k at the right of way ij: 1 for building, 0 for not building
M	Disjunctive factor for line ij, a positive big number
c_{ij}	Investment cost of the line ij
P_{ij}^{k}	Active power flow of branch k connecting bus i to *j*
k^{max}	Maximum number of candidate transmission lines per corridor
$\boldsymbol{L1}$	Matrix of contingencies that specifies the status of lines under different contingencies: 1 for in service, 0 for out of service lines
P_{ijc}^{k}	Active power flow of branch k connecting bus i to j in state *c*
δ_{ic}	Voltage angle at bus *i* in state c

1 Introduction

The energy transition is creating completely new challenges for the transport of electricity since the structure of power generation is changing. In particular, the electricity generated in Germany by wind farms in the north has to be transported to the major power consumption regions in the west and south, which may lead to the grid capacities being exceeded. Furthermore, electricity is increasingly generated by decentral wind, solar, and biomass installations on distribution grid level, adding further challenges to the electricity grid [1, 2]. Therefore, both the expansion and restructuring of power grids are necessary to cope with increasing shares of renewable generation.

The main purpose of transmission expansion planning (TEP) in power systems is to ascertain an optimal strategy to expand the existing transmission network to meet the demand of loads subject to a set of economic and technical constraints [3]. The TEP problem is a large-scale, non-linear and non-convex optimization problem, which is complex to solve. The real planning process involves a series of studies to decide how many transmission facilities are needed, where they should be installed, and when is the best time to install them [4].

A major factor in the operation and planning of a power system is the desire to keep system security. System security comprises practices designed to maintain the system operating when components fail. Security measures are important because a forced outage of a component might cause a system blackout. For instance, in the case of transmission lines, when a single line outage occurs due to an insulation failure, the power flow from the now-opened line is redistributed to the other lines in the power network. If one of the remaining lines is then too heavily loaded it may open due to relay action and, in the worst case, a cascading failure and system collapse could occur [5].

Not every single-line outage endangers other lines in the system, only some specific ones do. Some line power flows may be heavily affected due to the electric proximity to the disconnected line. To know the line outage impact on the power system, the so-called contingency analysis is carried out as part of the security assessment. An important tool for contingency analysis is the use of Line Outage Distribution Factors (LODFs), which estimate the power flow redistribution after a line outage [6, 7].

Adding contingency analysis to the TEP makes it more complex and mostly unsolvable for large-scale power systems. Most references that discuss optimization-based approaches to TEP ignore contingency constraints to make this large and complex problem solvable [4]. The N-1 criterion states that the planned network must be able to operate in a way that a single outage in a system component does not interrupt supplying demands [8]. Various researchers use either N-1 criterion or probabilistic approaches for power system security evaluation creating a security-constrained TEP (SC-TEP) [4, 9].

In the research field of energy system analysis, models are used for the optimization of power systems, which include grid expansion planning. One of these models is the energy system optimization model (ESOM) REMix developed at DLR, which is a modeling framework that allows the user to set up optimization problems written in GAMS addressing real-world power systems [10]. Nevertheless, REMix does neither consider the effects of security constraints on transmission line expansion nor contingency analysis on the power flow distribution. The objective of this work is therefore to better understand the necessity of taking these effects into account for ensuring a secure power supply in future power systems. The detailed objectives are explained below.

1.1 Research objectives

The main aim of this thesis is the analysis of the effects of transmission line outages in the network power flow and the adaption of the transmission capacity expansion planning to also consider the impact of single-line outages. To achieve this purpose, the following specific objectives have been formulated:

- Implementation of a line outages algorithm in a GAMS model using data of generic networks
- Setting up an instance of REMix using data of generic networks
- Implementation of an algorithm for line outages in REMix
- Determination of line expansion scenarios
- Adaption of the line outage algorithm to also model line expansion
- Validation of the new methods implemented in REMix
- Comparison of different TEP methods with and without security constraints

1.2 Thesis structure

This thesis is divided into 5 chapters. The current chapter presents an overview of the motivation for the study and introduces the objectives of this thesis. Chapter 2 comprehends a literature review of relevant topics including optimal power flow, contingency analysis, line outage distribution factors, and transmission expansion planning.

In chapter 3, the methodology is detailed giving an introduction of REMix and an explanation of the methods used for modeling the linear optimal power flow, the post-contingency critical lines (PCL) algorithm, TEP, and the integration of line expansion with the PCL algorithm.

Chapter 4 describes the results of the previously mentioned models tested on the IEEE RTS 24-bus network and two modified versions of this network. The validity of the proposed methods is also discussed in this chapter. Finally, the research conclusions are presented in Chapter 5 along with the scope for future work in this field.

2 Theory

This chapter presents the theoretical background of different concepts and formulations needed to understand the development of this thesis: Optimal Power Flow (OPF), contingency analysis, Line Outage Distribution Factor (LODF), and Transmission Expansion Planning (TEP).

2.1 Optimal power flow

The optimal power flow problem (OPF) is an optimization problem that has been studied since the 60's due to its importance in power system operation and planning [11]. The OPF problem is a combination of economic dispatch (explained by Wood et al. [5]) and power flow simulation. In consequence, the OPF determines the best operating point for electric power generators in order to meet demands given throughout transmission and distribution networks, subject to system constraints, usually with the objective of minimizing operation and maintenance costs [5, 7].

The OPF is used for scheduling generators for long and short-term power system planning. With advances in optimization tools, several new objectives and constraints are included in a traditional OPF problem, such as security constraints, active power loss, emission of generating units, number of control actions, and load shedding [7, 11].

Due to the non-linearity of power-flow equations for alternating current (AC) networks, OPFs are originally formulated as non-linear, non-convex optimization problems. Hence, finding a global optimum for the non-linear problem is challenging and computationally expensive [12].

For computational efficiency, the NLP problem is usually formulated with a linearized transmission model often referred to as the linear optimal power flow (LOPF) problem. Linearizing the load flow equations in transmission networks with sufficient reactive power compensation introduces only small errors [12, 13]. The LOPF is used in this thesis specifically the DC optimal power flow (DCOPF) and its detailed explanation is given in the following subsection.

2.1.1 DC optimal power flow

The DCOPF is a linear problem whose convexity guarantees that a local optimum is a global optimum. In consequence, it gives a good approximation to the AC optimal power flow (ACOPF), being much faster and easier to set up and solve [5].

Thanks to its simplicity and linearity the DCOPF is used in many types of studies, e.g. contingency analysis due to the multiple calculations required for checking the $N-1$

criterion and techno-economic studies of power systems for assessing the influence of commercial energy exchanges on active power flow in the transmission network [13].

The linearity of the DCOPF is achieved by making some assumptions: the reactive power is disregarded, a flat voltage profile consideration i.e. voltages magnitudes set to 1 p.u., line resistance is negligible, tap settings are ignored and voltage angle differences are small, i.e. $sin(\delta_{12}) \approx \delta_{12}$ [14].

The DCOPF gives no data about the voltage magnitudes, reactive power flows, or apparent power flows. However, it allows calculating a good approximation of active power flows on transmission lines and transformers, with an accuracy of 5% with respect to the ACOPF [5, 13]. The optimization problem of the DCOPF which should be solved is formulated as follows [6]:

$$\min \mathrm{OF} = \sum_{g \in \Omega_G} c_g P_g \tag{1}$$

where g is an index over the generators and $c_g P_g$ is the cost function for each generator of the system, where c_g is the fuel cost and P_g is the active power generated by generator g. This objective function is subject to:

$$P_{ij} = \frac{\delta_i - \delta_j}{x_{ij}} \quad \forall\, ij \in \Omega_l \tag{2}$$

$$\sum_{g \in \Omega_G^i} P_g - L_i = \sum_{j \in \Omega_l^i} P_{ij} \quad \forall\, i \in \Omega_B \tag{3}$$

$$-P_{ij}^{max} \leq P_{ij} \leq P_{ij}^{max} \quad \forall\, ij \in \Omega_l \tag{4}$$

$$P_g^{min} \leq P_g \leq P_g^{max} \quad \forall\, g \in \Omega_G \tag{5}$$

The first constraint, equation (2), corresponds to the DC power flow linearization with the assumptions described above, where δ_i is the voltage angle in bus *i* and x_{ij} is the reactance of the branch connecting bus *i* to *j*. The equation (3) is the bus power balance at each bus *i* related to Kirchhoff's Current Law indicating that the difference between generation (P_g) and the electrical load (L_i) must be equal to the power current P_{ij} withdrawn by each branch $j \in \Omega_l^i$ attached to the bus *i* [12].

Furthermore, equation (4) corresponds to the active power flow limits of each branch, and equation (5) denotes the maximum and minimum limits of power generation for each generator.

2.2 Contingency analysis

Contingency analysis is the study of the outage of elements such as transmission lines, transformers, and generators, and its effects on line power flows and bus voltages of the remaining system. It allows to analyze the power system security during planning and operation. Contingencies may cause severe violations of the operating constraints. Therefore, planning considering contingencies forms an important aspect of secure operation allowing the system to be operated defensively [15].

Transmission-line outages and generation-unit failures are two major types of failure events studied on contingency analysis. This thesis is focused on transmission-line outages, which affect all flows nearby the disconnected line. The outage's result could be a line flow limit or bus voltage limit violation.

The transmission system operator must know which line outages will cause flow or voltage limit violations. Contingency analysis techniques are used to predict the effects of outages, modeling single failure events or multiple failure events (i.e., two or more transmission lines). Some techniques simulate "all credible outages" and for each outage tested, the contingency analysis procedure checks all line flows and bus voltages in the network against their respective limits [5].

The most difficult problems to cope with in contingency analysis are the speed of solution of the model used and the selection of "all credible outages." Considering a system of around five thousand lines, if all possible outages were to solve in 1s, it would take more than 1h to obtain the report of all cases.

Due to long processing times, some contingency analysis techniques use a selection or ranking to determine the outage cases that cause the worst overloading problems and to check the system flows just for these important cases.

2.2.1 Contingency selection

Electrical engineers used to use their judgment and experience for selecting and analyzing critical contingencies. Nevertheless, this approach may not identify all severe contingencies, especially in large systems. Consequently, contingency selection is carried out for quickly identifying those contingencies which may cause overloading of lines. Hence, it is reduced the number of contingencies that need to be analyzed by full load flow while assessing the power system's security [3].

According to the state of art [16, 17], there are two main methods for contingency selection: ranking methods and screening methods. The advantages and disadvantages of these methods will be described below.

2.2.2 Ranking methods

Ranking methods order contingencies based upon their relative severity. Contingencies are ranked based on the performance index (PI), which measures the system stress based on different parameters. The PIs are explicitly expressed in terms of network variables such as the active power flows or voltages and are directly evaluated. Several PI-based methods have been proposed and tested for power system security analysis; for instance, some of them measure the degree of line overloads [18], some determine the bus voltages and other ones use the line current [19].

One of the disadvantages of the ranking methods is the masking effect that is the lack of discrimination because the PI value of a case with many high loadings but no violations is comparable with the index for a case with one huge violation [20]. Additionally, another important disadvantage is the misranking of contingencies, which is mainly due to the inaccuracies in the model used for calculating the PIs and refers to errors in the order of relative severity of some contingencies [16].

In recent years, some ranking methods using new approaches were developed, such techniques include artificial neural networks, genetic algorithms, or pattern recognition [16, 21, 22]. Generally, these methods have higher accuracy for the contingencies ranking and faster analysis times, although they may have hardware dependence due to the processing requirements.

2.2.3 Screening methods

The power flow solution approximation is used on screening methods to eliminate non-critical contingencies. The network parameters are first calculated for all the contingencies and ranking is done based on the results of the approximate solutions.

Screening methods, though more demanding in CPU resources, permit the identification of limit violations and the contingency selection using a more reliable technique and, therefore avoid masking or misranking errors [23]. Some of the methods include distribution factors, DC load flow, one iteration of AC load flow, and local solution methods.

A screening method using Line Outage Distribution Factors (LODF) is presented in this thesis and its formulation is explained in the next numeral. A summary of the contingency selection methods is shown in Figure 1.

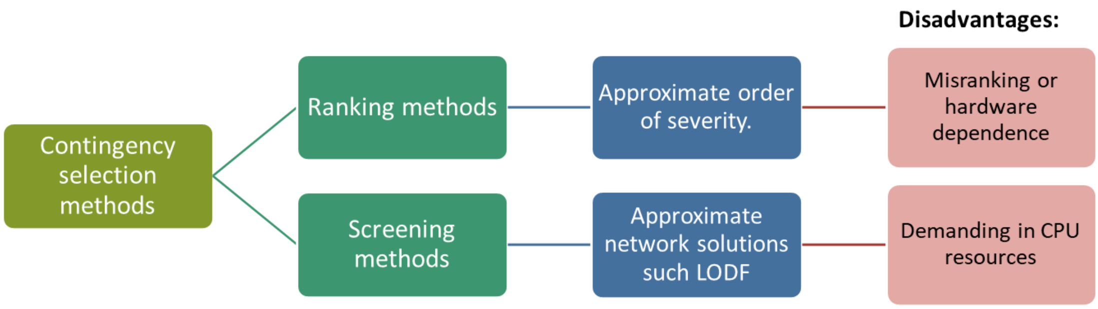

Figure 1 Contingency selection methods

2.3 Line Outage Distribution Factors

Line Outage Distribution Factors (LODF) measure the linear sensitivity of active power flows to outages of specific lines, providing a quick calculation of possible overloads. LODF estimate the steady-state power flow redistribution after a line outage and are derived from the load flow [6, 7].

The LODF used in this thesis are limited by the conditions of a DC power system model [24]:

a. All the voltages are considered to have a 1 p.u. magnitude.
b. The line resistance is disregarded since it is small compared to the line reactance. The shunt reactance is omitted.
c. The reactive power flow is neglected.

The advantages of the LODF are the high calculation speed, the accuracy for contingency selection in comparison with the ranking methods, and the obtention of approximate solutions for all the single line contingencies.

2.3.1 LODF formulation

In order to explain the mathematical definition of LODF Figure 2 shows an exemplary power system, on which the effect of the outage of the line nm connecting bus n to bus m is studied.

Suppose the flow of this line is initially equal to f_{nm}^{0}. Assuming no losses, this power flow is the same that is injected to bus n from the rest of the network and equal to the power absorption from bus m to the rest of the network when no contingency has happened.

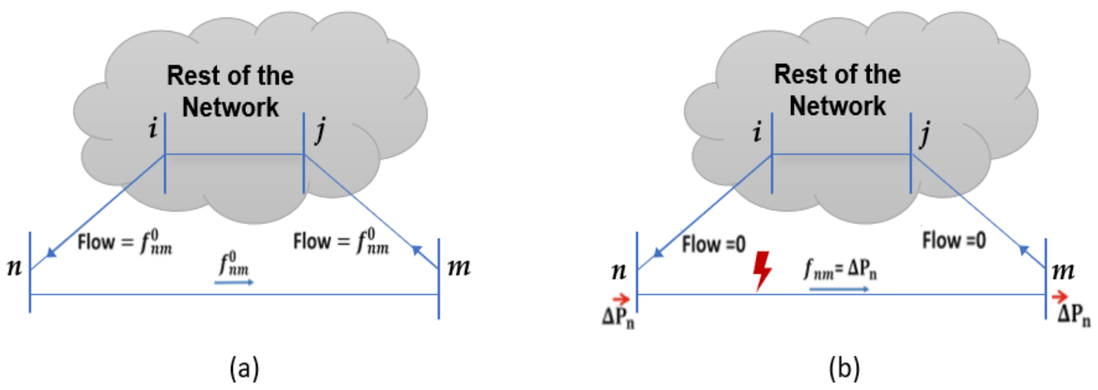

Figure 2. Line outage modeling using virtual injections. (a) Pre-contingency network (b) Post-contingency network. Adaption of [6].

After the contingency between bus n and m, f_{nm} will be zero. However, two virtual injections are added to simulate the opening of the line nm: $+\Delta P_n$ at bus n and another one equal to $-\Delta P_n$ at bus m. The power flow on the line nm would change as shown in Figure 2b [6] [5].

The virtual injection ΔP_n to the grid will be equal to the post-contingency line flow which is calculated as follows:

$$\Delta P_n = f_{nm}^{post} = f_{nm}^0 + \Delta f_{nm} \tag{6}$$

The change of flow on line nm can be calculated using the following equation:

$$\Delta f_{nm} = \frac{\Delta\delta_n - \Delta\delta_m}{x_{nm}} = \frac{X_{nn}\Delta P_n + X_{nm}\,(-\Delta P_n) - (X_{mn}\Delta P_n + X_{mm}\,(-\Delta P_n))}{x_{nm}} \tag{7}$$

Where x_{nm} is the reactance of the line nm, $\Delta\delta$ is the change of the bus voltage angle and X_{**} are values of the reactance matrix.

The previous equation could be reduced to:

$$\Delta f_{nm} = \frac{X_{nn} + X_{mm} - 2 * X_{nm}}{x_{nm}} \Delta P_n \tag{8}$$

Combining the equations (6) and (8) results:

$$\Delta P_n = \frac{f_{nm}^0}{\left(1 - \frac{X_{nn} + X_{mm} - 2X_{nm}}{x_{nm}}\right)} \tag{9}$$

On the other hand, the change in the power flow of line ij is calculated as follows:

$$\Delta f_{ij} = \frac{\Delta\delta_i - \Delta\delta_j}{x_{ij}} = \frac{X_{in} - X_{im} - X_{jn} + X_{jm}}{x_{ij}} \Delta P_n \tag{10}$$

Therefore, in this case the LODF corresponding to the impact of an outage on line nm on the power flow of line ij could be obtained combining equations (9) and (10):

$$LODF_{ij,nm} = \frac{\Delta f_{ij}}{f_{nm}^0} = \frac{X_{in} - X_{im} - X_{jn} + X_{jm}}{x_{ij}\left(1 - \frac{X_{nn} + X_{mm} - 2X_{nm}}{x_{nm}}\right)} \tag{11}$$

2.3.2 *Calculation of approximate flows using LODF*

The flow of line ij with line nm out can be determined using LODF [6, 25]:

$$f_{ij}^C = f_{ij}^0 + LODF_{ij,nm} f_{nm}^0 \tag{12}$$

Where:

- f_{ij}^0 , f_{nm}^0 are respectively the pre-outage flows on lines ij and nm.
- f_{ij}^C is the post-outage flow of line ij with line nm out.

2.4 Transmission expansion planning

In recent years, the massive integration of renewable energy resources has given more importance to the reliability and efficiency of power systems. The reliable and efficient operation of a power system largely depends on optimal transmission grid planning.

Transmission expansion planning (TEP) determines the least costly strategy to expand the existing transmission network with the aim of facilitating energy exchange among producers and consumers while maintaining the reliability and security performance of the power system [3].

Some of the motivations for TEP are the aging of the current infrastructure, expected load growth, and the new renewable generation facilities, usually located far away from demand centers. Therefore, it is essential to reinforce and expand the existing transmission network in order to guarantee energy flows from generators to consumers. These demands must be supplied even in the worst situations, such as a peak load or the failure of a generating unit [26].

2.4.1 *Classification of TEP formulations*

In general, TEP is a complex decision-making problem because it involves a multi-criteria objective, non-linear constraints, and a non-convex feasible region. Consequently, many approaches have been proposed to solve it. Those approaches can be classified from different viewpoints [26, 27].

From the viewpoint of power system uncertainties, TEP approaches can be classified in:

- Deterministic: For these approaches, the expansion plan is designed only for the worst-case scenario, for example with a load that corresponds to the maximum load demand expected in the planning horizon. The deterministic approaches do not consider the probability of occurrence of different scenarios.
- Non-deterministic: these approaches are able to consider uncertainties associated with the analysis of the random and nonrandom factors in the TEP formulation. Some uncertainty parameters considered are loads, prices, renewable energy generation, availability of generating units, among others [27].

Considering the implementation horizon, TEP approaches are classified into:

- Static: these methods assume that system expansions are implemented instantly at a single point in the future. The optimal design could include grid topology, transmission capacities, or a set of possible reinforcements to achieve a particular objective [28].
- Dynamic: considers temporal continuity of expansion project with multi-year planning. The dynamic approaches make the transmission expansion decisions at different points in time of the planning horizon. Besides, they provide more economically efficient solutions since it allows the transmission planner to adapt to future changes in the system, although they are computationally intensive [26, 28].

In this thesis, a deterministic and static approach to the TEP problem is used and its mathematical formulation is explained in numeral 3.4.1.

2.4.2 Methods for solving TEP

The aim in the TEP problem is to find the solution that gives the optimal objective function value and satisfies the constraints. Being a very complex problem, different methods have been developed for solving TEP, the most relevant are based on exact or heuristics optimization algorithms [28].

Exact optimization algorithms are the traditional ones, which can prove the optimality of the solution found. The most common exact methods comprise linear programming [29, 30], nonlinear programming [31] , mixed-integer programming [3] [32], bilevel programming [33], and decomposition techniques [34]. In the development of this thesis, a mixed-integer linear programming algorithm is used.

Heuristic algorithms have been developed to cope with the complexity of the TEP problems, providing a feasible solution with less computational effort than exact algorithms. The heuristic methods correspond to experience-based techniques that are inspired by learning processes of nature, industry, or phenomena [3, 28, 35].

Moreover, the heuristic algorithms usually use a sensitivity index, define a set of rules or perform local searches with some logical guidelines specified to find a solution to the TEP. The drawbacks of the heuristic methods are the impossibility to prove that the feasible solution is optimal and the propensity to get stuck in local minima or even diverge [28, 36].

2.4.3 The mixed-integer linear programming model

The classical mathematical model for TEP problems is based on a mixed-integer nonlinear programming (MINLP) model [3, 37]. For a DC flow model, the nonlinearity is due to constraints related to the power flow equations, where bus voltage angle variables are multiplied by line investment binary decision variables [38]. However, the MINLP problems are difficult, if not impossible to solve [32], which means a simplification is needed.

The mixed-integer linear programming (MILP) problems are linear optimization models in which only some of the variables are constrained to be integers, while other variables are allowed to be continuous [39]. It is possible to reformulate the original non-linear TEP problem as a MILP problem without introducing additional approximations using the disjunctive method discussed in [32]. The mathematical formulation of the MILP TEP problem of this thesis is presented in the methodology, specifically in section 3.4.1.

3 Methodology

The aim of this master thesis is to model line outages and to integrate the security effects of such line outages into the TEP problem which is part of an existing energy system optimization framework called REMix-MISO. This section will present the methodology used for achieving these objectives, whose schematically representation is shown in Figure 3.

First, for validation purposes, a DCOPF problem of a generic electrical system is developed from scratch using GAMS [40]. In the following, this model is called the “Validation model”. The same system is parameterized for solving it using REMix-MISO. Secondly, the method for post-contingency analysis of critical lines (PCL) using LODF is applied to the generic system modeled in the previous stage, this method is presented in section 3.3.

The next step is the modeling of two TEP scenarios for a generic electrical network. These scenarios are implemented in REMix-MISO and validated with the “Validation model”. Finally, the line expansion model is adapted to include security constraints with the PCL algorithm. The REMix modeling framework used in this thesis and each of the previously mentioned steps will be explained in detail below.

Figure 3. Project methodology

3.1 REMix-MISO

The modeling framework REMix-MISO is developed at the DLR and written in GAMS. It allows the user to set up different energy systems optimization problems and is programmed in a modular structure with a high geographical and technological flexibility. Regarding the geographical aspect, all modules can be applied to regions of all sizes, ranging from small cities to world regions. Thus, it allows to optimize in hourly resolution the operation of an energy system and to determine the least-cost future expansions [10].

The framework REMix-MISO is designed with a feature-centric approach as presented in Figure 4, including blocks of conversion, transport, storage, sources, and sinks. Additionally, commodities and indicators are important concepts used on MISO to model the energy systems [41]. The previously mentioned features are explained below.

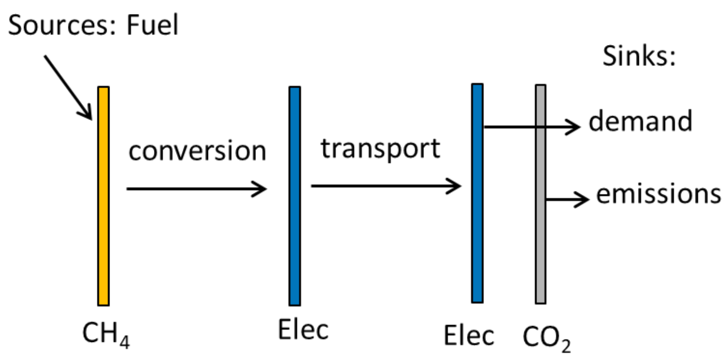

Figure 4. Scheme with the general features of REMix-MISO. Adapted from [41]

3.1.1 Concepts

REMix-MISO has the advantage of allowing modeling energy systems of different carriers (e.g. electricity, gas, etc.) and accounting for different indicators (e.g. costs, CO2, etc.). of the system. For this reason, the concept of commodities and indicators is essential in REMix-MISO.

3.1.1.1 Commodities

The commodities in REMix-MISO trace physical flows of energy carriers (e.g. fuels, electricity, heat, etc.). They have dedicated sources and sinks. Inside the system, they can be stored, transported, and converted into other commodities [41].

3.1.1.2 Indicators

For accounting purposes, different indicators can be used (e.g. costs, firm capacities, land use, CO2, etc.). They account for non-physical or non-restricted flows and are calculated based on associated generator units, lines, activities, and sources. Indicators can be accounted for a single or multiple-year period. Likewise, they can be considered across single model nodes, globally, or according to custom regions [42].

3.1.2 REMix-MISO modules

REMix-MISO consists of several modules as represented in Figure 5. Currently, there are three so-called framework modules, seven core modules, and six methods modules. The framework modules give a general structure to the model, specifically, the "framework_miso" module defines the MISO model calling the model definition of each of the core modules and including the files of the solving methods. A brief description of the core modules is presented below.

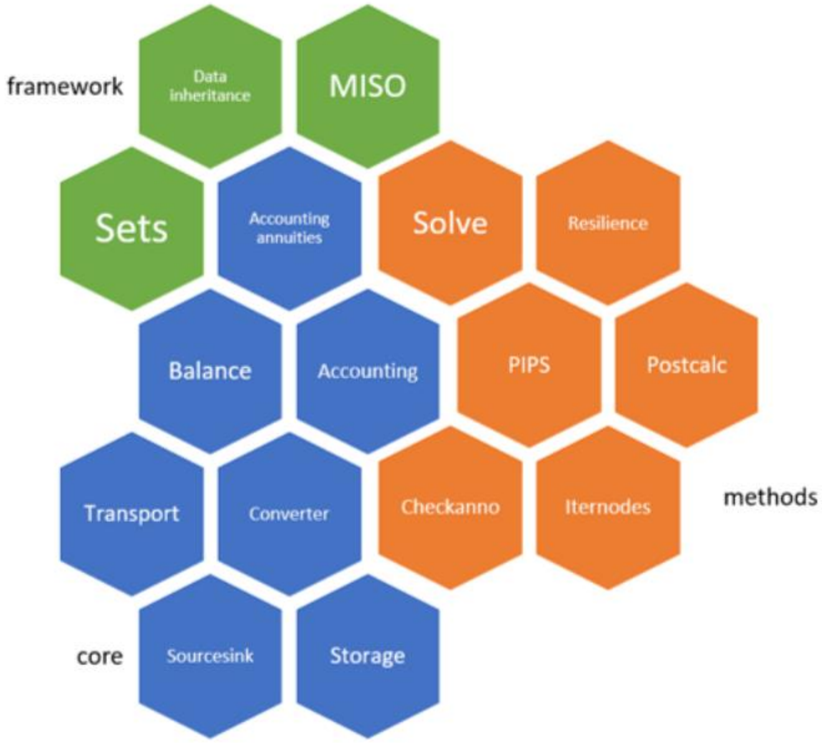

Figure 5. Modules of REMix-MISO. Source: [43]

3.1.2.1 Converter

Converters are technologies that allow conversion processes from one commodity to another commodity. They are modeled including their technical characteristics, which are processed in the "core_converter" module, and their economical parameters, which are inputs for the "core_accounting" module. The conversion activities associated with the converters describe the ratios between input commodities and output commodities. A converter can have one or multiple conversion activities (e.g. generation of power and generation of heat) [41].

Examples of the converters that are possible to consider in the REMix simulations are wind turbines, photovoltaic systems, conventional power plants, combined heat and power (CHP), among others.

3.1.2.2 Transport

The commodity transport among regions is implemented in REMix-MISO with corridors. First, the initial and final regions of each corridor are defined, these connections can be of any commodity. Afterward, the commodity transported through each corridor is specified (e.g. electricity, heat, gas, etc.) and its technical characteristics such as losses, rated capacity, and reactance.

The energy flows through the corridors are usually bidirectional, but can also be defined as unidirectional, which is especially of relevance for gas grids or HVDC power lines. For the electrical networks, REMix-MISO optimizes power transmission through a LOPF. There are two LOPF methods already implemented in REMix-MISO, one is a DCOPF that uses voltage angles and another that uses Kirchhoff cycles. Code extensions related to security-constrained TEP have not been available in this module yet and need to be implemented.

3.1.2.3 Storage

Storage technologies allow a commodity to be stockpiled for a period of time, which depends on its technical features such as the rated capacity. In MISO, the storage technologies are generally built using two different components: a storage reservoir to keep the chosen commodity and a converter for charging and discharging the storage [41].

3.1.2.4 Sources and sinks

Sources and sinks represent the inputs and outputs of the physical commodities to the system respectively, for example, a source could be a fuel imported from a global market and a sink could be emissions into the environment. Moreover, it is possible to limit the hourly or annual availability of fuels or emissions [41].

3.1.2.5 Balance

The balance module in MISO makes the energy balance for each commodity used in each period of time, region, or node of the system and year. This module ensures that the demand is met at all times and in all regions.

3.1.2.6 Accounting

The definition of the objective function to minimize is made in the “core_accounting” module, the inputs of this module are the accounting parameters for the converters, transport, storage, and source/sinks. The objective function is defined depending on the indicators specified by the user. Usually, the overall system costs are defined as objective function and minimized.

3.2 DCOPF for a generic network

In this stage, a generic electrical network is modeled and the DCOPF is calculated using the Validation model and REMix-MISO.

3.2.1 IEEE RTS 24-bus system

The generic network chosen is the IEEE Reliability Test System (RTS) 24-bus network [6]. Figure 6 shows its single line diagram. The IEEE-24 system used in this thesis has 34 branches, 12 generators, 17 loads, and 24 buses.

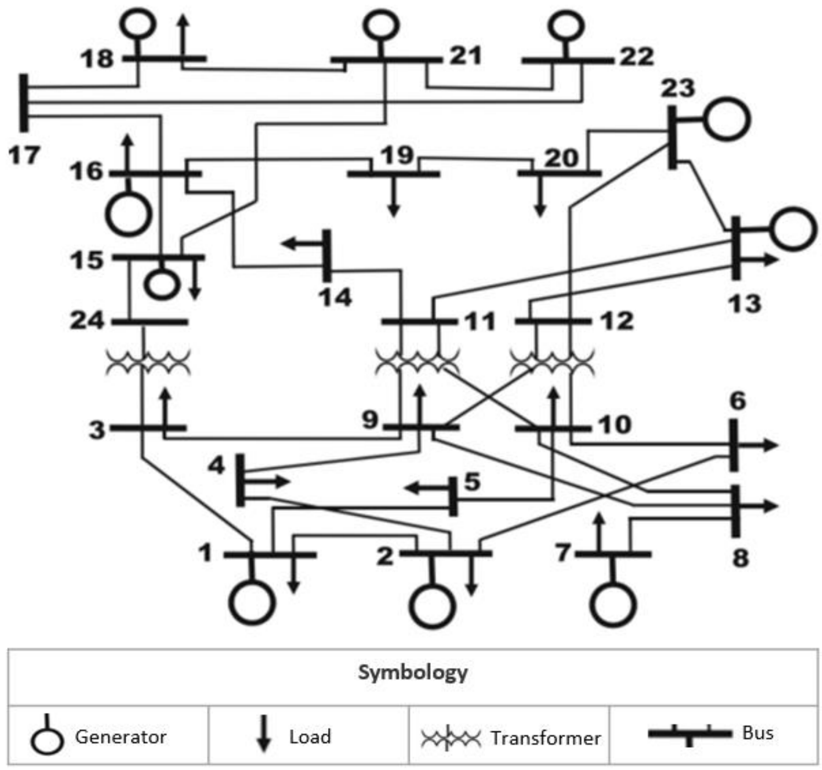

Figure 6. IEEE RTS 24-bus network. Adapted from [6].

The generation data for the IEEE RTS 24-bus network is presented in Table A1 of Appendix A. The slack bus is bus 13 in this network. The data of generating units is obtained from Soroudi [6]. The total load of the system is 2850 MW. The characteristics of the loads are given in Table A3.

The transmission lines are at two voltage levels, 138kV and 230kV with S_{base} = 100MVA. The 230-kV system is the top part of Figure 6, with 230/138 kV tie stations at buses 11, 12, and 24. Branch parameters are given in Table A2.

3.2.2 DCOPF using the Validation model

The Validation model is a simple model of the IEEE RTS 24-bus system created in GAMS that allows validating the results obtained with REMix-MISO. It uses per unit values to represent the reactances of the branches.

The DCOPF for the IEEE 24-bus system is implemented in the Validation model using the equations (1) to (5). It represents a simplified version of the source code example provided by Soroudi [6].

3.2.3 DCOPF of the IEEE RTS 24-bus system in REMix-MISO

To use the model framework REMix-MISO it is necessary to set up an instance with the technical and economical parameters. In this case, the parameters of the IEEE RTS 24-bus network are set up using Python, the steps are shown in Figure 7 and detailed below.

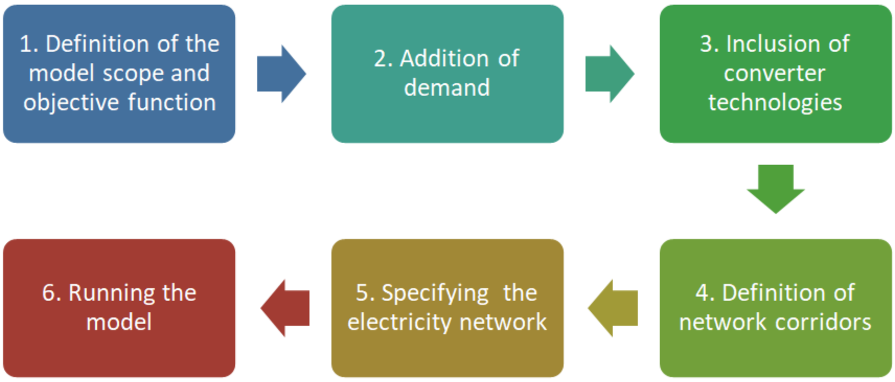

Figure 7. Method for DCOPF using REMix-MISO

3.2.3.1 Definition of the model scope and objective function

The definition of the model scope and objective function indicates the spatial and temporal scopes of the model. For this system, the 24 nodes are added and the optimization is set up to one hour. In this case, the objective is the minimization of the total system cost.

3.2.3.2 Addition of demand

The hourly load indicated in Table A3 is added, modeling one hour and using the format required by REMix-MISO, which includes setting the demand as negative values.

3.2.3.3 Including converter technologies

To add converter technologies in REMix-MISO it is necessary to specify the produced commodity, the technical and economical parameters, and the activities the technology can perform. In this case, the produced commodity is electricity. The technical and economical parameters are indicated in Table A1 and the activity is the power generation. The estimated lifetime of the generating units is 25 years.

3.2.3.4 *Definition of network corridors*

For the network corridors definition, the link connections are set up specifying the start and end points of each line. Additionally, the terrain type and length of each line need to be specified. The terrain type is *land* for all lines and the length is calculated based on the reactance with the equation (13). To calculate the lengths of the lines, the reactance per distance ($x_{d_{ij}}$) is set to 10 $\Omega/$km. The lengths used for each line are given in Table A4 of Appendix A.

$$d_{ij}\ [\text{km}] = \frac{x_{ij}\ [\Omega]}{x_{d_{ij}}\ [\Omega/\text{km}]} \tag{13}$$

3.2.3.5 *Specifying the electricity network*

The electricity network is added specifying that the commodity is electricity, the technical and economical parameters shown in Table A2, and the reactance in Ohms presented in Table A4 and calculated with equation (14). This equation is obtained combining per unit equations presented by Kasikci [44].

$$x_{ij} = \frac{{U_{base}}^{2} * x_{ij\ pu}}{S_{base}} \tag{14}$$

Moreover, for running the DCOPF in REMix-MISO it is necessary to define the parameter “gridSegments”. This parameter defines a group of links for which dc-power flow equations should be applied.

3.2.3.6 *Running the model*

The final step before running the model is collecting the data frames created during the previous steps and converting them to .dat files, which are used for the modeling framework REMix-MISO to optimize the system. For the running of the model some solver settings can be defined (e.g. epgap, crossover, etc.). In this case, the default settings are used and the results of the optimization correspond to the DCOPF.

3.3 Post-contingency critical lines (PCL) algorithm

To find the critical lines after a contingency $N-1$, a post-contingency critical lines (PCL) algorithm is implemented for both the Validation model and REMix-MISO. Figure 8 shows the flowchart of this algorithm.

Basically, the algorithm initiates constructing the matrix of Susceptance (**B**), which corresponds to the imaginary part of the nodal admittance matrix (**Y** Matrix). The **B** matrices are usually always singular, i.e. not invertible, its reduction is therefore needed. $\mathbf{B_{reduced}}$ is determined by choosing an arbitrary non-zero reference node and removing its corresponding row and column of the **B** matrix [45].

Next, the algorithm calculates the LODF using equation (11) and the approximate post-contingency power flows using equation (12). Next, the absolute values of the matrix of the estimated post-contingency flows ($\boldsymbol{F}_{ij}^{C}$) are subtracted from the values of the rated capacity matrix ($\boldsymbol{P}_{ij}^{max}$). If the difference is less than or equal to zero, the outage case will be part of the critical cases matrix ($\boldsymbol{CC}_{ij,nm}$), and each outage case will take a value of one.

The next stage is the construction of the critical lines list (CL_{nm}), which contains the lines on outage causing an overload on the network and the number of cases in which each line causes a limit violation. To calculate the critical lines, the critical cases are added for all supervised lines (ij) as shown in equation (15).

$$\boldsymbol{CL_{nm}} = \sum_{\boldsymbol{ij}} \boldsymbol{CC_{ij,nm}} \tag{15}$$

Finally, the three top critical lines are chosen according to the number of cases in which each line causes an overload in the system.

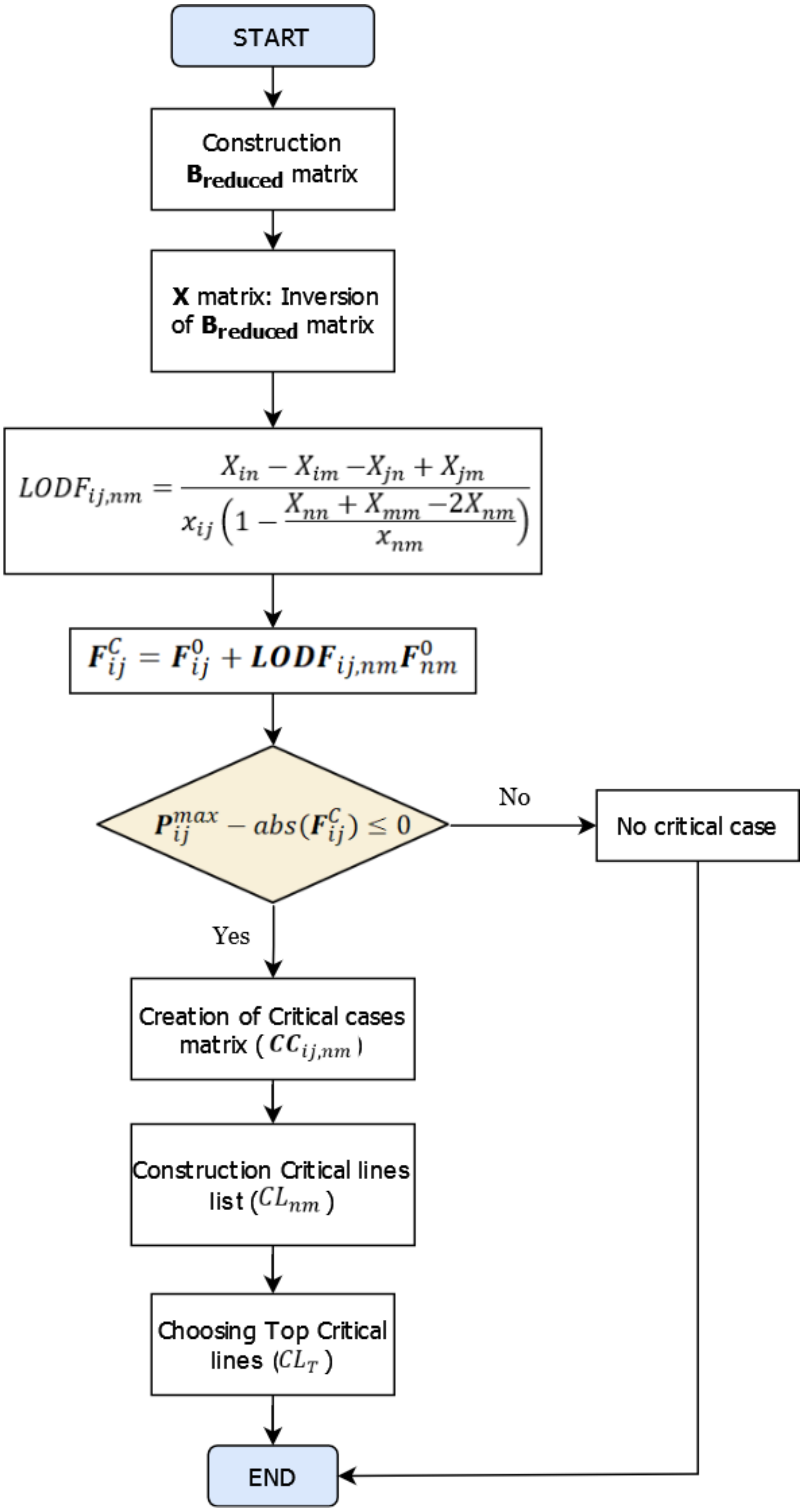

Figure 8 Flowchart of the post-contingency critical lines algorithm

3.3.1 Implementation of the PCL algorithm in REMix-MISO

The post-contingency critical lines algorithm is applied to the IEEE RTS 24-bus system modeled in the previous stage using the Validation model and REMix-MISO.

The modeling in the Validation model is simpler than in REMIx-MISO because this model has just one module and the per unit values are used. On the other hand, REMix-MISO has several modules with different purposes as explained above.

As consequence, the construction of the $\boldsymbol{B_{reduced}}$ matrix, its inversion, and the LODF calculation are made in the "core_transport" module. The calculation of the estimated post-contingency flows ($\boldsymbol{F}_{ij}^{C}$) and subsequent steps to find the critical lines are implemented in a new method called "methods_LODF".

The validation of the PCL algorithm is made by comparing the estimated post-contingency power flow ($\boldsymbol{F}_{ij}^{C}$) with the real optimal power flow after the outage of some lines and with the results of the literature [6]. Additionally, the critical lines results obtained in the Validation model and REMix-MISO are compared to each other.

3.4 Method for modeling TEP

The next stage of this thesis is the modeling of two scenarios of transmission expansion planning (TEP) by modifying the initial data of the IEEE RTS 24-bus system in order to obtain a system that requires a network expansion. To achieve this, both the Validation model and REMix-MISO are extended according to the following problem formulation.

3.4.1 Problem formulation

The static TEP is formulated as a mixed-integer linear problem and represents a modified version of the one suggested in [30] and [6]. The formulation is presented in equations (16) to (24).

The main aim of TEP is to find the best scenario of transmission expansion that minimizes the sum of transmission investment costs (c_{ij}) and generation operating costs (c_g) in a given network. The objective function, equation (16), assumes that only investments in new electricity lines are possible. In this formulation, α_{ij}^{k} is the binary variable to model the investment decision regarding the line k at the right of way ij.

$$\min \mathrm{OF} = \sum_{g \in \Omega_G} c_g P_g + \sum_{k,ij} c_{ij} \alpha_{ij}^{k} \qquad (16)$$

The objective function is subject to the following constraints:

$$\sum_{g \in \Omega_G^i} P_g - L_i = \sum_{j \in \Omega_l^i} P_{ij} \quad \forall\, i \in \Omega_B \tag{17}$$

$$P_{ij}^k - B_{ij}(\delta_i - \delta_j) \leq (1 - \alpha_{ij}^k)\mathrm{M} \quad \forall\, ij \in \Omega_l \tag{18}$$

$$P_{ij}^k - B_{ij}(\delta_i - \delta_j) \geq -(1 - \alpha_{ij}^k)\mathrm{M} \quad \forall\, ij \in \Omega_l \tag{19}$$

$$-P_{ij}^{max}\alpha_{ij}^k \leq P_{ij}^k \leq P_{ij}^{max}\,\alpha_{ij}^k \quad \forall\, ij \in \Omega_l \tag{20}$$

$$P_g^{min} \leq P_g \leq P_g^{max} \quad \forall\, g \in \Omega_G \tag{21}$$

$$B_{ij} = \frac{1}{x_{ij}} \tag{22}$$

$$\alpha_{ij}^k \in \{0,1\} \tag{23}$$

$$k \in \{1, \dots, k^{max}\} \tag{24}$$

The constraint (17) corresponds to the power node balance applying the first Kirchoff's law. The inequalities (18) and (19) represent the second Kirchoff's law for each candidate line. In these constraints, a disjunctive factor (M) is introduced to get rid of the nonlinearities of the flow expression caused by the product of continuous variables (P_{ij}^k) and binary variables (α_{ij}^k) as proposed by [46] and [32].

When a candidate line binary variable (α_{ij}^k) is set to one in the constraints (18) or (19), the DC line flow equation is forced to hold, while if it is set to zero the disjunctive constraints enforce that no flow will go through the circuit [32]. Consequently, M should be assigned with a sufficiently large value that provides enough degree of freedom to the voltage angle difference between every unconnected node of the network. However, it is important to consider that a M factor that is too large will sometimes cause numerical difficulties [3, 30]. As defined by Soroudi [6], in this thesis the big M is selected as follows:

$$M = max_{ij}\left(B_{ij}(\delta_i - \delta_j)\right) \approx max_{ij}(B_{ij} * \pi * {}^{4}/_{3}) \tag{25}$$

The line flow limits including the impact of the line investment binary variable are depicted for the constraint in (20). The generation operating limits are shown in (21). The susceptance definition is given in (22).

The constraint (23) indicates the possible values of the binary variable (α_{ij}^k), 1 if line k is built, 0 if not. Finally, the constraint (24) corresponds to the number of possible candidate lines k to construct per corridor and k is an integer parameter.

When the DCOPF equations are used directly to make the line expansions, the non-linearity is because the power flow influences the investment decisions of lines per corridor, but these investment decisions influences the reactance per corridor (x_{ij}), i.e. **B** matrix. However, the susceptance matrix, in turn, influences the power flows, which again influences investment decisions. For this reason, the DCOPF included until now in REMix-MISO does not consider the change of the reactance when two or more lines are in parallel. One of the contributions of this thesis is the inclusion of a MILP TEP method in REMix-MISO, which contemplates the effect of parallel reactances on the line expansion.

3.4.2 Definition of TEP scenarios

Considering the IEEE RTS 24-bus network presented in the sub-section 3.2.1 with 34 corridors, some modifications are made to the system to turn it into a TEP problem. The investment costs presented in Table 1 are proportional to the reactance of every line and are those provided by Alguacil et al. [30]. Additionally, it is assumed that all the lines of the same corridor have the same characteristics.

Table 1. Investment cost and line capacities for Scenarios A and B, based on [30].

Corridor	Investment Cost [Million US$]	Scenario A Capacity [MVA]	Scenario B Capacity [MVA]	Corridor	Investment Cost [Million US $]	Scenario A Capacity [MVA]	Scenario B Capacity [MVA]
1-2	7.04	175	58.33	**11-13**	24.10	500	166.67
1-3	106.92	175	58.33	**11-14**	21.16	500	166.67
1-5	42.78	175	58.33	**12-13**	24.10	500	166.67
2-4	64.14	175	58.33	**12-23**	48.90	500	166.67
2-6	97.20	175	58.33	**13-23**	43.79	500	166.67
3-9	60.24	175	58.33	**14-16**	19.70	500	166.67
3-24	42.47	400	133.33	**15-16**	8.76	500	166.67
4-9	52.50	175	58.33	**15-21**	24.81	1000	333.33
5-10	44.70	175	58.33	**15-24**	26.27	500	166.67
6-10	30.63	175	58.33	**16-17**	13.11	500	166.67
7-8	31.08	175	58.33	**16-19**	11.70	500	166.67
8-9	83.58	175	58.33	**17-18**	7.29	500	166.67
8-10	83.58	175	58.33	**17-22**	53.31	500	166.67
9-11	42.47	400	133.33	**18-21**	13.11	1000	333.33
9-12	42.47	400	133.33	**19-20**	20.05	1000	333.33
10-11	42.47	400	133.33	**20-23**	10.93	1000	333.33
10-12	42.47	400	133.33	**21-22**	34.32	500	166.67

Two scenarios for the TEP are considered, namely, scenario A and scenario B. In scenario A, the initial system has no preinstalled lines, the rated capacities are the same that for the base case system and it is possible to build two lines per corridor ($k^{max} = 2$). The number of binary variables in this scenario is 68.

In scenario B, the initial network topology is the one shown in Figure 6, and a maximum of four lines ($k^{max} = 4$) per corridor is admitted. To allow investment decisions, the maximum capacity of each line is reduced to one-third of the base case capacity as shown in Table 1. The number of binary variables is 136, four times the number of corridors. A constraint is included that sets $\alpha_{ij}^{k=1} = 1$ in this scenario.

3.4.3 *Modeling TEP scenarios in the Validation model*

For the Validation model, two different GAMS files are created based on the initial IEEE RTS 24-bus system, one for each scenario. The branch parameters are modified and the investment costs are added using the information in Table 1. Moreover, the equations (16) to (25) are included for each file.

3.4.4 *Modeling TEP scenarios in REMix-MISO*

For each scenario the parameters detailed in Table 1 are set up using one Python script, using the same method detailed in sub-section 3.2.3.

Initially, the line expansion method included in REMix-MISO is used to compare the results of the Validation model. However, it is necessary to implement a mixed-integer linear TEP method to obtain comparable results.

The "core_transport", "core_balance" and "core_accounting" modules are modified to implement the MILP TEP method in MISO. A new "opfmethod" called "angle_mip" is included in the "core_transport" module considering the equations (18) to (25) and using the previous parameters and variables of REMix-MISO. For the "angle_mip" method the "core_balance" module is modified so that the line power flow depends on whether the line is built or not in case k. The "core_accounting" module is extended for the "angle_mip" method using the equation (16).

Finally, the comparison between the results of the Validation model and REMix-MISO is made for scenarios A and B.

3.5 Method for integration of line expansion and PCL algorithm

The last methodological step of this thesis is the integration of the TEP with the post-contingency critical lines (PCL) algorithm, creating a security-constrained TEP (SC-TEP). Typically, the SC-TEP evaluates all the possible single outages to comply with the $N-1$ criterion [3, 47]. However, the addition of all contingencies into MIP has significant impacts on computational effort and simulation time [4]. The mathematical formulation of the proposed SC-TEP is presented in the first sub-section, followed by the description of the integrated method workflow. Finally, the modeling differences for REMix-MISO and the Validation model are explained.

3.5.1 Mathematical formulation of SC-TEP

A security-constrained mixed-integer linear formulation for the static TEP is presented in equations (26) to (33). This formulation is a modified version of the one suggested in [3] and [4]. The objective function, equation (26), is the same that for the TEP without considering contingencies.

$$\min \text{OF} = \sum_{g \in \Omega_G} c_g P_g + \sum_{k,ij} c_{ij} \alpha_{ij}^k \tag{26}$$

Subject to:

$$\sum_{g \in \Omega_G^i} P_g - L_i = \sum_{j \in \Omega_l^i} P_{ijc} \quad \forall\, i \in \Omega_B \tag{27}$$

$$P_{ijc}^k - B_{ij}(\delta_{ic} - \delta_{jc}) \le (1 - z_{ij}^k)\text{M} \quad \forall\, ij \in \Omega_l \tag{28}$$

$$P_{ijc}^k - B_{ij}(\delta_{ic} - \delta_{jc}) \ge -(1 - z_{ij}^k)\text{M} \quad \forall\, ij \in \Omega_l \tag{29}$$

$$-P_{ij}^{max} z_{ij}^k \le P_{ijc}^k \le P_{ij}^{max} z_{ij}^k \quad \forall\, ij \in \Omega_l \tag{30}$$

$$P_g^{min} \le P_g \le P_g^{max} \quad \forall\, g \in \Omega_G \tag{31}$$

$$z_{ij}^k = \begin{cases} \boldsymbol{L1} & \text{for existing lines} \\ \alpha_{ij}^k \boldsymbol{L1} & \text{for new lines} \end{cases} \tag{32}$$

$$k \in \{1, \dots, k^{max}\} \tag{33}$$

In this SC-TEP problem, constraint (27) guarantees the power balance at every bus, considering the contingency cases for the power flow of the line. The disjunctive factor M explained in the sub-section 3.4.1 is included in constraints (28) and (29). In this problem the variables i.e. P_{ijc}^k, δ_{ic}, and δ_{jc} have to be calculated for every contingency case.

The line flow limits including the impact of the line investment binary variable and the matrix of contingencies are provided in constraint (30). The limit on generation dispatch is shown in constraint (31).

The constraint (32) indicates that the problem includes normal and under single contingency states of the system. In this formulation, $\boldsymbol{L1}$ represents a contingency scanning matrix to model the considered contingencies. A 0 in this binary matrix means the line is on outage and 1 means that the lines are in normal service [3].

The columns of the contingency matrix are called states (c). The first column of $\boldsymbol{L1}$ in equation (34) represents the normal operating condition with all lines in service, and one line is on outage in each next column of the matrix. For the proposed method the lines on outage will be the ones indicated by the top critical lines list CL_T.

$$\boldsymbol{L1} = \left[\begin{array}{c|ccc} 1 & 0 & \cdots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \cdots & 0 \end{array}\right] \tag{34}$$

3.5.2 Workflow of the integrated method

Considering that the single outages of some lines will not cause limit violation on other lines, the proposed SC-TEP method includes only the critical contingencies into TEP. The flowchart in Figure 9 shows a summary of the following steps of the proposed SC-TEP:

- Step 1: The input data of loads, generation units, current, and candidate transmission lines is loaded to create the base case system. The base case system that contains existing lines, loads, buses, and generators is referred to as S_0.
- Step 2: A relaxed version of the TEP problem is solved ignoring all constraints related to the contingency analysis, according to the formulation described in sub-section 3.4.1. The selected candidate lines together with the existing network (N_0) form the updated network (N_1). The updated system is named S_1.
- Step 3: Using the information of the updated network (N_1) the top critical lines list (CL_T) is created with the post-contingency critical lines (PCL) algorithm detailed in sub-section 3.2. If CL_T is empty, it means the current network configuration satisfies the N-1 criterion and corresponds to the final solution. Otherwise, contingency matrix $\boldsymbol{L1}$ will be created based on CL_T.
- Step 4: For solving the SC-TEP optimization problem, the initial system S_0 is considered and the TEP problem is modified to include the contingency matrix $\boldsymbol{L1}$. The detailed mathematical formulation will be explained in the previous sub-section.

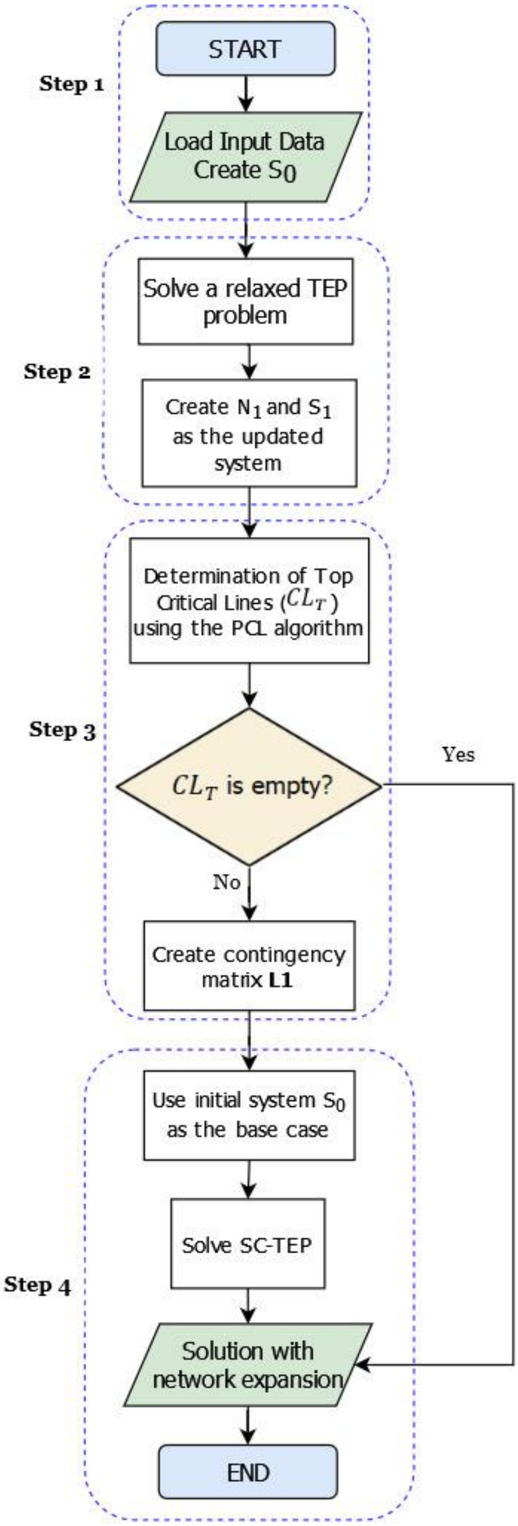

Figure 9. Flowchart of the method with the integration of line expansion and PCL algorithm

3.5.3 SC-TEP modeling

The proposed SC-TEP method is applied to scenario B of the IEEE RTS 24-bus system modeled in the previous stage (sub-section 3.4) using the Validation model and REMix-MISO.

For the Validation model, the GAMS file includes the equations (26) to (34) and two GAMS models are defined, one for the relaxed TEP problem and another for the SC-TEP problem.

For REMix-MISO, the "framework_miso" is modified to include a GAMS model for the SC-TEP problem, whose equations are mainly defined in "core_transport". Furthermore, the "methods_LODF" is integrated into a new module called "method_SC_TEP". In this method, the models for TEP problems defined in "framework_miso" are called.

4 Results and discussion

The results obtained in this project and its discussion will be presented in this chapter. The first section describes the linear optimal power flow results for the IEEE RTS 24-bus network to know the initial status of the network before outages, followed by the results of the post-contingency critical lines (PCL) algorithm showing the estimated post-contingency power flows and the critical lines, and the analysis of the TEP solution for the proposed scenarios. Finally, the outcome of the integrated line expansion algorithm with PCL is discussed considering the implications in supply security.

4.1 DCOPF for IEEE RTS 24-bus network

The results of the DCOPF with REMix-MISO are validated against the Validation model. For the validation of the generation at each node, the optimal cost, and the power flow on each line are compared.

The DCOPF cost for the IEEE RTS-24 bus system is 29574.27 Million US $. This total cost result is the same using the Validation Model and REMix-MISO. The detailed generation costs and power per node are given in Figure 10. As expected, generator 12 at node 22 is selected at its maximum capacity of 300MW due to its zero cost (parameters presented in Table A1). These generation results are the same as those already provided by Soroudi [6], confirming that the solution of the DCOPF is correct.

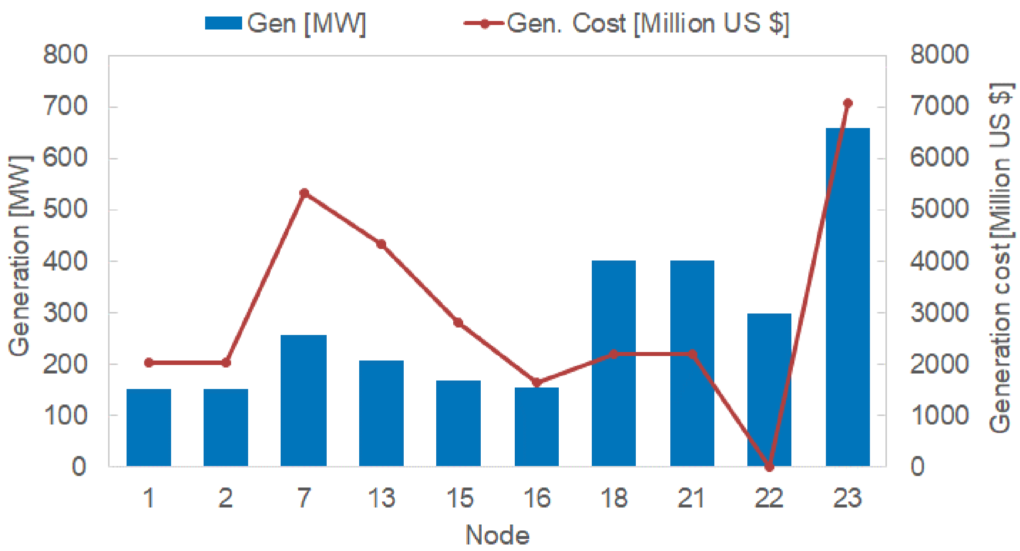

Figure 10. Generation solution for IEEE RTS 24-bus network

The results for the power flows of the transmission lines are given in Table 2, including the percentage of the maximum load for each line. The highest loads are at lines 7-8, 14-

16, and 16-17. These line power flows are equal for the Validation Model and REMix-MISO.

Table 2. Power flows for IEEE RTS 24-bus network

Line	P_{ij} [MW]	Load [%]	Line	P_{ij} [MW]	Load [%]
1-2	12.3	7%	11-13	92.7	19%
1-3	17.5	10%	11-14	169	34%
1-5	49.2	28%	12-13	65.8	13%
2-4	26.5	15%	12-23	226.5	45%
2-6	40.8	23%	13-23	216.7	43%
3-9	19.3	11%	14-16	363	73%
3-24	216.8	54%	15-16	80	16%
4-9	47.5	27%	15-21	446.8	45%
5-10	21.8	12%	15-24	216.8	43%
6-10	95.2	54%	16-17	320.2	64%
7-8	132.2	76%	16-19	92.2	18%
8-9	30.4	17%	17-18	179.4	36%
8-10	8.4	5%	17-22	140.8	28%
9-11	124.5	31%	18-21	112.4	11%
9-12	109.2	27%	19-20	88.8	9%
10-11	152.6	38%	20-23	216.8	22%
10-12	167.8	42%	21-22	159.2	32%

The principal difference between the results for DCOPF using the Validation model and REMix-MISO is the processing time, which is 0.063s for the first one and 2s for the second one. The longer computation time for REMix-MISO is mainly due to the modeling framework checks for some inputs that are not part of this IEEE-24 bus system such as storage, losses, and source/sinks parameters.

4.2 Post-contingency critical lines (PCL) algorithm

Using the method proposed in section 3.2 the matrices **LODF** and $\boldsymbol{F_{ij}^{C}}$ are obtained, each one with 1089 (33x33) entries. The estimated flow ($\mathrm{f_{ij}^{C}}$) of each single-line outage is divided by the corresponding thermal limit to obtain the percentage of load shown in Figure 11.

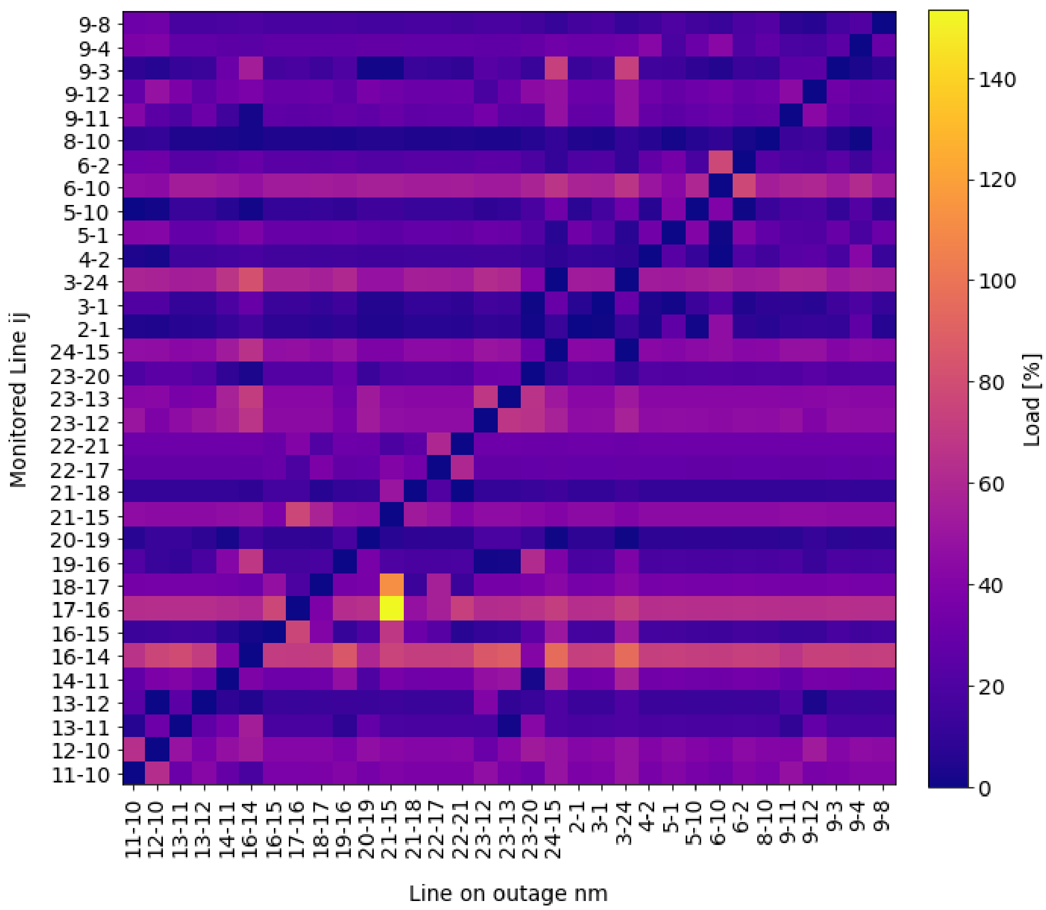

Figure 11. Post-contingency power flows for the IEEE RTS 24-bus system

Most of the single-line contingencies do not cause an overload of the lines as depicted in Figure 11, corresponding to a line load up to 40% of the thermal limit. Nevertheless, monitored lines 17-16 and 16-14 are highly loaded after many of the single-line outages. The detailed post-contingency power flows on lines 17-16 and 16-14 for all possible single-line outages are shown in Figure 12 and Figure 14 respectively.

For many of the outages, the post-contingency power flow on line 17-16 is at a similar level as the flow before the outage, i.e. 320MW as shown in Figure 12. However, the highest power flow of 767MW after the outage of line 21-15 exceeds the thermal limit and is represented in Figure 13.

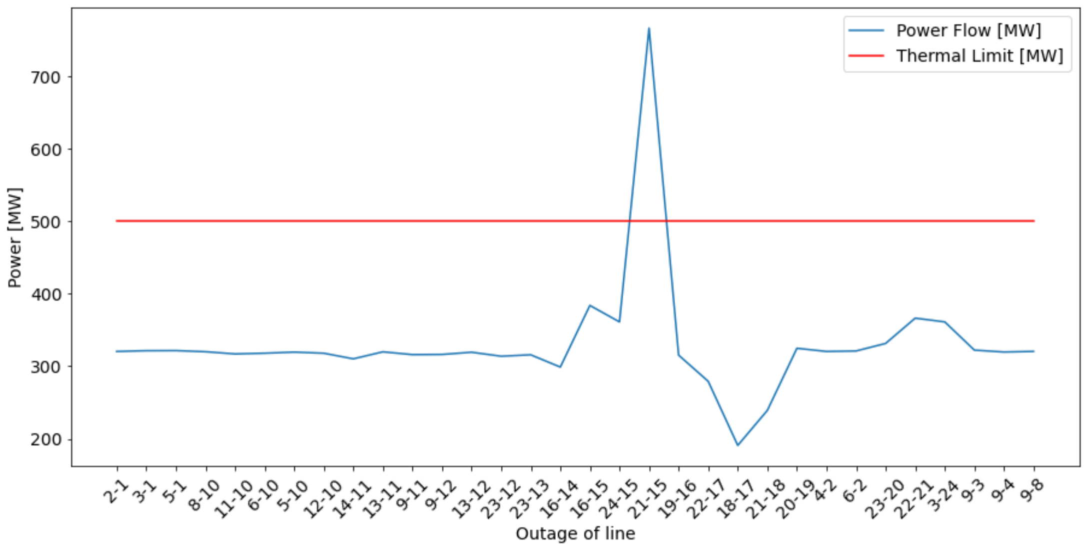

Figure 12. Post-contingency power flow on line 17-16

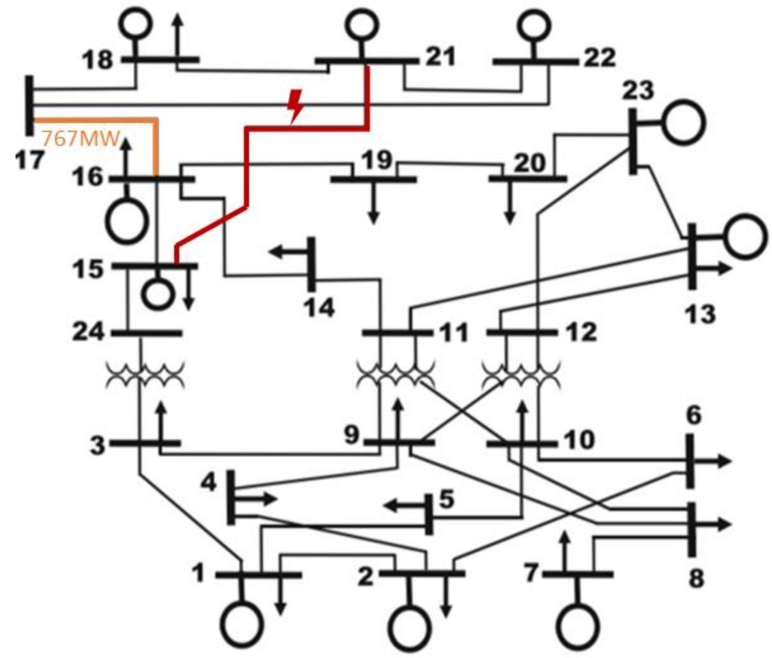

Figure 13. Representation of outage of line 21-15 for IEEE RTS 24-bus system

In Figure 14 the high variation of post-contingency power flow on line 16-14 is shown indicating the susceptibility of this line to the outages. For some outages, there is a significant increase in the power flow. The highest flow of 480MW occurs after the outages of the lines 24-15 or 3-24, corresponding to 96% of the load.

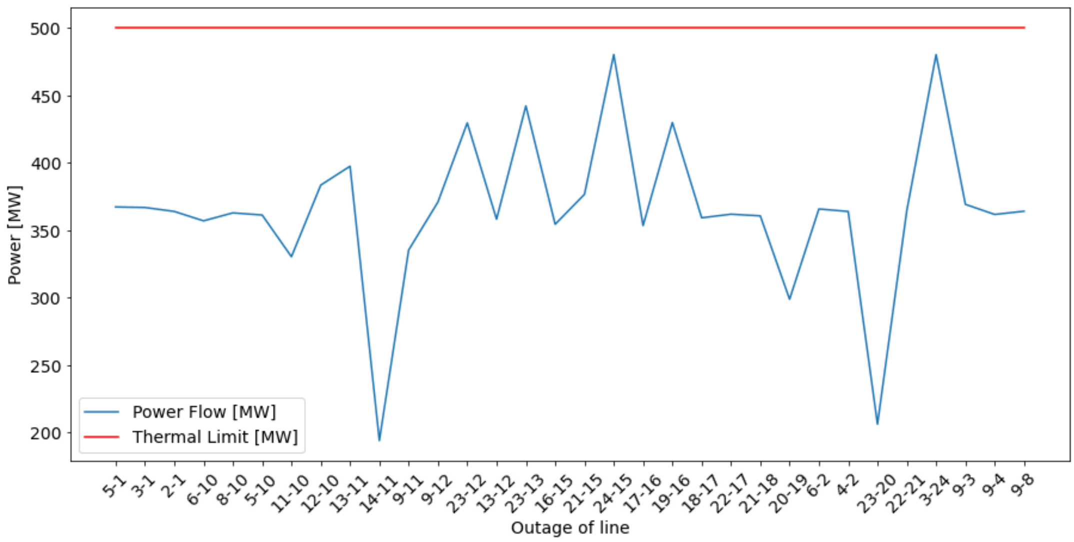

Figure 14. Post-contingency power flow on line 16-14

The critical cases matrix ($\boldsymbol{CC_{ij,nm}}$) is given in Table 3. For this IEEE RTS 24-bus systems, there are just two critical outages cases, which exceed the thermal limits. The most loaded line after a single-line outage is 17-16 with 153%, and the second-most loaded line is 18-17 with 113%. The PCL algorithm indicates that there is one critical line 21-15, whose outage causes an overload of the two lines described previously.

Table 3. Critical cases for IEEE RTS 2-bus network

Monitored line ij	Line nm on outage	Estimated Post-contingency flow f_{ij}^{C} [MW]	Thermal Limit [MW]	Load [%]
17-16	21-15	767	500	153%
18-17	21-15	565.2	500	113%

The LODFs and post-contingency estimated flows (f_{ij}^{C}) obtained with the PCL algorithm implemented in REMix-MISO and the Validation model based on [6] are highly similar, the highest relative error is 0.01%. This difference is due to some rounding approximations in REMix-MISO during the OPF calculation. The critical cases for both models are exactly the same.

4.3 TEP scenarios

The results of the two TEP scenarios are described and analyzed below.

4.3.1 Scenario A

Scenario A assumes that the initial network has no preinstalled lines. Table 4 illustrates the optimization results provided by both REMix-MISO and the Validation Model in terms of the number of lines built, investment cost, and power flows for the branches. The graphical representation of this scenario solution is given in Figure 15.

The total lines built are 22, which corresponds to 12 fewer lines than the original IEEE RTS 24-bus system. Nonetheless, these 22 lines have a higher load than the original system with a maximum of 87% for the lines 9-11 and 15-16. The solution of scenario A does not consider the interconnection of three buses (12, 13, 17) with the main grid as shown in Figure 15. Buses12 and 17 correspond to substations without generation or load, hence for a scenario without preinstalled transmission network, this would mean savings in the installation of new substations. This optimal solution excluding some nodes is similar to the solution presented by Alguacil [30].

On the other hand, the optimal solution for the bus 13 implies the isolation of its generation and load with the drawbacks associated such as management of energy reserves, security risks, and energy forecasting [48].

Table 4. TEP Solution for Scenario A – Lines

Corridor	# of new lines built	Investment cost [Million US $]	Absolute Power flow per line [MW]	Load [%]
1-2	1	7.04	55	31%
1-5	1	42.78	99	57%
3-24	1	42.47	180	45%
4-9	1	52.5	74	42%
5-10	1	44.7	28	16%
6-10	1	30.63	136	78%
7-8	1	31.08	74	42%
8-10	1	83.58	97	55%
9-11	1	42.47	346	87%
10-11	1	42.47	303	76%
11-14	2	42.32	325	65%
14-16	2	39.4	422	84%
15-16	1	8.76	437	87%
15-21	1	24.81	767	77%
15-24	1	26.27	180	36%
16-19	1	11.7	351	70%
18-21	1	13.11	67	7%
19-20	1	20.05	532	53%
20-23	1	10.93	660	66%
21-22	1	34.32	300	60%
Total	22	651.39		

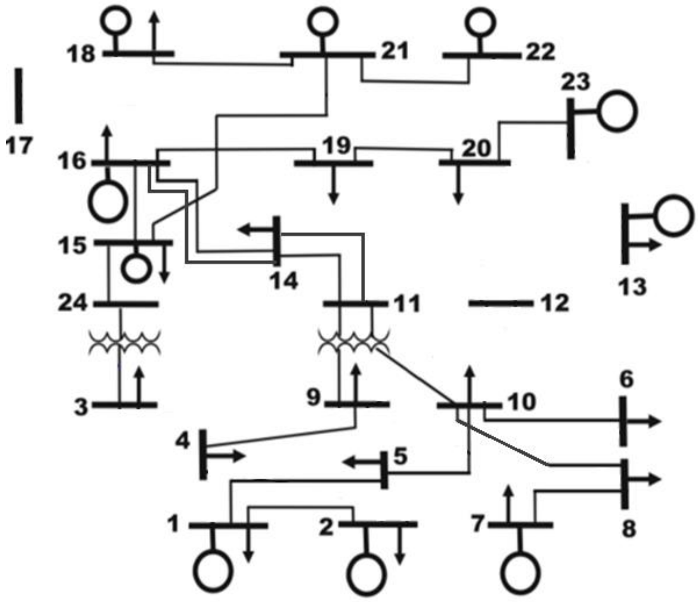

Figure 15. IEEE RTS 24-bus network solution for Scenario A

The total costs of scenario A are 30239 Million US $, of which 651.4 Million US $ correspond to transmission system investment costs as detailed in Table 4 and 29587.6 Million US $ are the operation costs for power generation detailed in Table 5.

Scenario A generation solution presented in Table 5 is the same as for the original IEEE 24-bus system except for nodes 7 and 13. The optimal generation at node 13 increases to produce exactly the load of this isolated node. As a consequence, the node 7 generation decreased to compensate for the increase in node 13.

Table 5. TEP Solution for Scenario A – Generation

Node	Generation [MW]	Operation cost [Million US $]
1	152	2024.6
2	152	2024.6
7	199	4119.3
13	265	5546.5
15	167	2793.3
16	155	1630.6
18	400	2188.0
21	400	2188.0
22	300	0.0
23	660	7072.7
	Total	**29587.6**

The TEP solution for scenario A is equal for the Validation model and REMix-MISO, and the processing times are 3.18s for the first one and 2.43s for the second one.

4.3.2 *Scenario B*

The rated capacity of each line of the IEEE RTS 24-system is reduced to one-third for scenario B. Table 6 shows the optimized solution from REMIx-MISO in terms of the number of new lines built, investment costs, and power flows for the lines. The graphical representation of the optimal solution for scenario B is given in Figure 16.

Table 6. TEP Solution for Scenario B – Lines

Corridor	# of new lines built	Investment cost [Million US $]	Absolute Power flow per line [MW]	Line Load [%]
3-24	1	42.47	120	90%
6-10	1	30.63	54	92%
7-8	1	31.08	58	100%
10-12	1	42.47	116	87%
12-23	1	48.9	145	87%
14-16	2	39.4	119	71%
15-21	1	24.81	236	71%
15-24	1	26.27	120	72%
16-17	1	13.11	147	88%
Total	10	299.14		

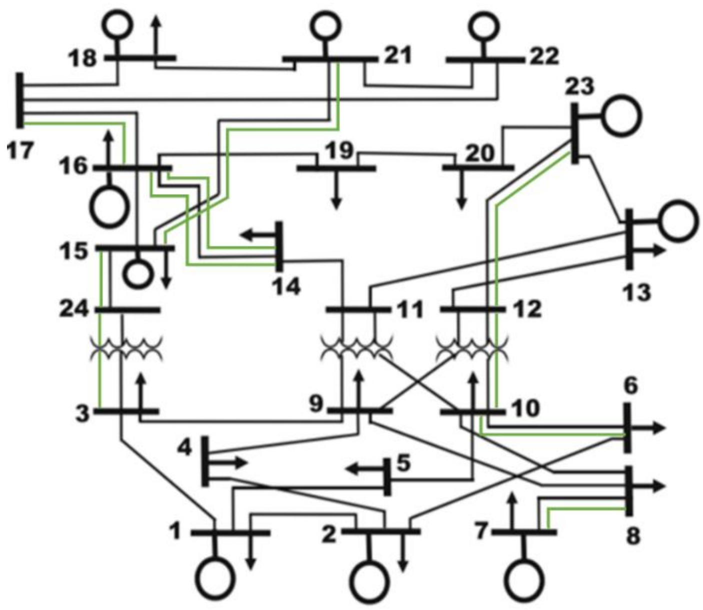

Figure 16. IEEE RTS 24-bus network solution for Scenario B

The number of new lines built is 10, including new lines for the corridors previously highly loaded according to the DCOPF presented in Table 2, i.e. 7-8, 14-16, 16-17.

However, the average load for these new lines is 84%, and the maximum load of 100% is fo line 7-8.

The total costs of scenario B are 29876.9 Million US $, of which 299.1 Million US $ correspond to lines expansion investment costs as detailed in Table 6 and 29577.8 Million US $ are the operation costs for power generation detailed in Table 7.

As in scenario A, the generation solution for scenario B is the same as for the original IEEE 24-bus system represented in Figure 10, except for nodes 7 and 13. As shown in Table 7, the optimal generation of node 13 increases by 15.5MW, whereas power generation of node 7 decreases by 15.5MW, which represents a small increment in the operation costs compared to the DCOPF presented in sub-section 4.1.

Table 7. TEP Solution for Scenario B – Generation

Node	Generation [MW]	Operation cost [Million US $]
1	152	2024.6
2	152	2024.6
7	241.7	5002.5
13	222.3	4653.4
15	167	2793.3
16	155	1630.6
18	400	2188.0
21	400	2188.0
22	300	0.0
23	660	7072.7
	Total	**29577.8**

The TEP solution for scenario B is very similar for REMix-MISO and the Validation model, with a maximum relative error in the power flow of 0.5% due to rounding approximations in REMix-MISO during the flow calculation.

The calculation time is 2.8s for the Validation Model and 7.5s for REMix-MISO. The longer processing time for REMix-MISO is mainly due to the additional checking of MISO for some inputs that are not included in the IEEE-24 bus system such as storage, losses, and source/sinks parameters.

4.3.3 TEP solution comparison with expansion planning of MISO

The line expansion method already included in REMix-MISO is called “angle method”. This method is based on the TEP linear programming method proposed by Villasana [29]. It is a deterministic and static method and with continuous variables only. Nevertheless, the optimal solution of this method differs significantly from the solution of the Validation model.

For this reason, the method “angle_MIP” is implemented using the formulation detailed in sub-section 3.4.1, obtaining results equals or very similar to the optimal solution of the Validation model.

The comparison of the optimal solution obtained with the “angle” and “angle_MIP” methods for the two scenarios is illustrated in Figure 17. For scenario A, the solution of “angle_MIP” lowers the cost by 655 Million US $ compared to the “angle” method. The “angle” method solution suggests the construction of 33 lines, whereas the “angle_MIP” method solution expands 22 lines.

For scenario B, the solution of “angle_MIP” decreases the cost by 115 Million US $ with respect to the “angle” method. The “angle” method solution suggests the construction of 14 new lines, whereas the “angle_MIP” method solution proposes 10 new lines.

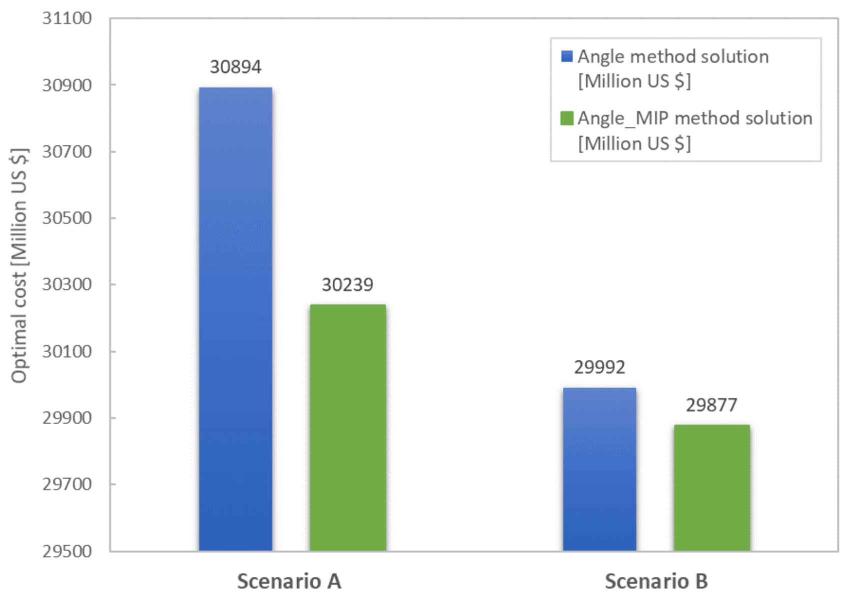

Figure 17. Comparison TEP solutions using Angle method and Angle_MIP method

The main reason for this difference is that for the corridors with more than one line the “angle” method does not consider the decrease of the reactance, which is applied to lines in parallel according to Ohm’s law. On the other hand, the “angle_MIP” method considers the reactance of the lines in parallel, when it calculates the second Kirchoff’s law for each candidate line (k) in the equations (18) and (19) in sub-section 3.4.1.

4.4 Integration of line expansion and PCL algorithm

The system of scenario B is used to analyze the results of the security-constrained proposed method, which integrates MILP-TEP and the post-contingency critical lines algorithm.

To show how the method works, the steps explained in section 3.5.2 are summarized for this system. Step 1: input data is loaded and S_0 is created; Step 2: the mixed-integer TEP problem is solved as detailed in sub-section 4.3.2. The selected lines are shown in the second column of Table 8, and S_1 is created; Step 3: the top critical lines list (CL_T) is created, its values are given in Table 9. As CL_T is not empty, the contingency matrix $\boldsymbol{L1}$ is constructed**;** Step 4: the SC-TEP optimization problem is solved with REMIx-MISO and the results are shown in the third column of Table 8.

Table 8. TEP with and without security constraints PCL, Scenario B of IEEE 24-bus system

	Without security constraints	**With security constraints of PCL**
Selected Lines	3-24	3-9
	6-10	3-9
	7-8	6-10
	10-12	6-10
	12-23	7-8
	14-16	7-8
	14-16	9-11
	15-21	10-12
	15-24	11-14
	16-17	12-23
	-	14-16
	-	14-16
	-	15-16
	-	16-17
	-	16-17
	-	16-17
	-	17-18
	-	17-18
	-	17-18
	-	18-21
Total new lines	10	20
Total Cost [Million US $]	29877.13	31616.56
Investment Cost [Million US $]	299.14	521.37
Operation Cost [Million US $]	29577.99	31095.19

Table 9. Top critical lines for Scenario B

Critical Line on outage	# Overloaded lines
3-24	7
15-24	7
15-21	6

First, the impact of considering security constraints obtained with the PCL on the TEP compared to ignoring it is evaluated. As shown in Table 8, in the case with security constraints ten extra lines are needed and the additional investment costs compared to the TEP without security constraints are 222.23 Million US $. The graphical representation of the optimal solution for the SC-TEP of scenario B is given in Figure 18. The top critical lines are 10% of the total critical lines, in this case, corresponding to 3 critical lines as shown in Table 9. The number of overloaded lines caused by the outage of each of the top critical lines is presented in Table 9. An overload of a transmission line brings about the tripping of its overcurrent protection, leading to load shedding with its associated costs. Therefore, the additional investment costs for security are justified by the operation cost savings related to the overloaded lines, one example calculation is given by Majidi-Qadikolai [4].

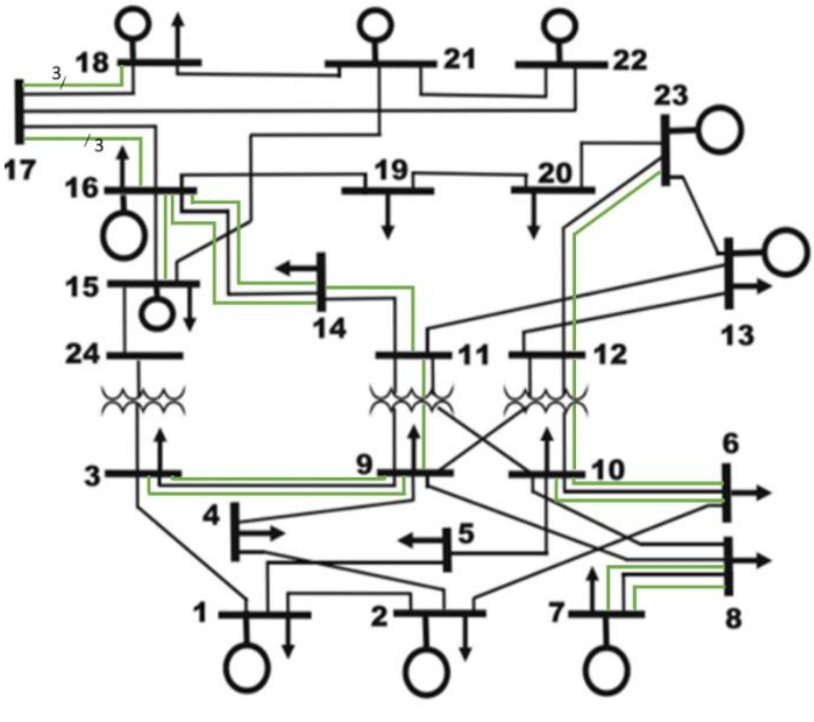

Figure 18. IEEE RTS 24-bus network solution for Security-Constrained Scenario B

Moreover, the SC-TEP considering all possible single-line contingencies ($N-1$ criterion) is also solved to compare its result and processing time with the proposed method. The final results are given in Table 10. The proposed SC-TEP using the top critical lines selected 20 new lines and the SC-TEP with all contingencies selected 44 lines.

The last row of Table 10 shows the total optimization time. The proposed security-constrained method with critical lines is around 146 times faster than the SC-TEP considering all possible outages.

Table 10. TEP with security constraints of PCL vs full N-1 criterion for Scenario B

	With security constraints of PCL		**With full $N-1$ criterion in TEP**				
Selected Lines	3-9	14-16	1-2	5-10	10-11	14-16	17-22
	3-9	14-16	1-5	6-10	10-12	15-16	18-21
	6-10	15-16	2-4	6-10	10-12	15-21	20-23
	6-10	16-17	2-6	8-9	11-13	15-24	21-22
	7-8	16-17	2-6	8-9	11-14	16-17	
	7-8	16-17	3-9	8-10	12-13	16-17	
	9-11	17-18	3-9	8-10	12-23	16-17	
	10-12	17-18	3-24	9-11	12-23	16-19	
	11-14	17-18	3-24	9-12	13-23	17-18	
	12-23	18-21	4-9	10-11	14-16	17-18	
Total new lines	20		44				
Total Cost [Million US $]	31616.6		32904.7				
Investment Cost [Million US $]	521.4		1748.9				
Operation Cost [Million US $]	31095.2		31155.8				
Calculation time [min]	4.6		676.9				

Considering the selected lines and cost difference between the solution with three critical lines and the application of the full $N-1$ criterion, the proposed method is tested using different percentages of the critical lines as the top lines for security constraints. The results are given in Table 11. As expected, the total cost and processing time increase with more top critical lines, but the total cost difference compared to the full $N-1$ criterion decreases.

If all the critical lines are considered, 28 lines, in this case, the power system will be secured from all single-line contingencies that might overload the network. However, the proposed method gives a solution that is not completely secure for all possible single-line contingencies. The total cost difference decreases to 1.5% and the calculation time is around 5 times faster than the SC-TEP considering the full $N-1$ criterion.

Even non-critical line outages have an influence on the optimized line expansion. However, considering them in the optimization increases the calculation time significantly. Depending on the level of supply security that should be achieved the SC-TEP method only considering the top critical lines could be used as an accelerated approximation of a N-1 secure energy system.

The rate of critical lines to consider in the SC-TEP depends on the desired level of supply security, which is affected by the associated costs. Nevertheless, as mentioned by the Federal Ministry for Economic Affairs and Energy: "Identifying the optimum level of supply security for the economy is a challenging undertaking" [49].

Table 11. Integrated SC-TEP method for different rates of critical lines for Scenario B

% of critical lines	Number of critical lines	Time [min]	Total Cost [Million US $]	Investment Cost [Million US $]	Total new lines	Total cost difference
10%	3	4.6	31617	521	20	3.9%
20%	6	30.5	31828	712	26	1.8%
100%	28	138.0	32412	1297	39	1.5%
Full N-1 criterion (34 lines)		676.9	32904	1749	44	

5 Conclusion

This thesis analizes the effects of transmission line outages in the system power flow using the Line Outage Distribution Factors (LODF) and integrates these effects in the transmission expansion planning (TEP) with a method that includes a security-constrained TEP model (SC-TEP) using the critical lines.

The post-contingency critical lines (PCL) algorithm is implemented using LODF to find the critical lines of a power system after a single-line contingency. The estimated post-contingency power flows ($\boldsymbol{F}_{ij}^{C}$) are calculated with the LODF. The critical cases matrix ($\boldsymbol{CC}_{ij,nm}$) is created considering all the $\boldsymbol{F}_{ij}^{C}$ that exceed the thermal limits of line ij. Next, the critical lines list (CL_{nm}) is constructed with the lines on outage causing an overload on the network.

The algorithm is applied on the IEEE RTS 24-bus system with 34 lines using the REMix-MISO framework model. The PCL results show that most of the single-line contingencies do not cause an overload of the lines of this network under normal operation conditions. The LODF and $\boldsymbol{F}_{ij}^{C}$ obtained in REMix-MISO are validated with the Validation model implemented in GAMS, with very similar results with 0.01% as the highest relative error.

To create a SC-TEP, two scenarios of a static mixed-integer linear formulation of TEP are modeled by modifying the initial data of the IEEE RTS 24-bus system in order to obtain a system that requires a network expansion.

Scenario A assumes that the initial IEEE RTS 24-bus network has no preinstalled lines and it is possible to build two lines per corridor. The solution comprises the building of 22 transmission lines, which corresponds to 12 fewer lines than the original power system. The TEP solution for scenario A in REMix-MISO is the same as the result obtained with the Validation model.

Scenario B supposes that the rated capacity of each line of the IEEE RTS 24-system is reduced to one-third and a maximum of four lines ($k^{max} = 4$) per corridor can be built. The number of new lines built is 10 and the average load for these new lines is 84% of their thermal limit. The TEP solution for scenario B is very similar for both REMix-MISO and the Validation model, with a maximum relative difference of 0.5%.

A systematic method to integrate critical contingencies into TEP is proposed considering that in most cases of contingency analysis, it is not necessary to evaluate all lines because the single outage of some lines will not cause overload on other lines. The proposed method solves the relaxed MILP-TEP problem, applies the PCL algorithm to the expanded power system identifying critical lines, and solves a SC-TEP adding constraints based on these critical lines.

The proposed security-constrained line expansion has been tested on scenario B of the IEEE RTS 24-bus system. The results using 10% of the top critical lines show that 10 extra lines are required in comparison with the TEP solution without security constraints. Ignoring security analysis in TEP may cause load shedding and huge extra operation costs when a critical line outage occurs.

The proposed method is tested using different percentages of the critical lines for security constraints, this percentage corresponds to the top critical lines. The results show that the total cost, the selected lines, and processing time increase with more top critical lines, but the cost difference compared to the full $N-1$ criterion decreases, by a minimum of 1.5% when all critical lines are considered. This difference shows that the proposed method gives a solution that is not completely secure for all possible single-line contingencies

The use of the proposed method makes it possible to include contingency analysis into TEP and significantly reduces processing time compared to the application of the full $N-1$ criterion in TEP, i.e. more than 146 times faster for 10% of the critical lines and 5 times faster for 100% of the critical lines. Depending on the desired level of supply security the SC-TEP method only considering the top critical lines could be used as an accelerated approximation of a N-1 secure energy system.

In this thesis, the modeling framework REMix-MISO is improved with the addition of the MILP-TEP method called “angle_MIP” which considers the reactance of lines in parallel, and the security-constrained TEP method called “method_SC_TEP” which integrates the critical contingencies of the power system.

In future research, the integrated security-constrained method could be tested with bigger networks, a real network, or for longer time horizons. Further economical constraints related to the supply security as the value of loss load should be added to the TEP to obtain more conclusive economic results. Moreover, a probability factor could be included in the proposed SC-TEP method to consider the unscheduled outage probability in the grid expansion.

6 Appendix A – Parameters for IEEE RTS 24-bus network

Table A1. Generating units parameters for IEEE RTS 24-bus network [6].

Gen	Bus	Pmax [MW]	Pmin [MW]	c_g [Million US $/MW]
g1	18	400	100	5.47
g2	21	400	100	5.47
g3	1	152	30.4	13.32
g4	2	152	30.4	13.32
g5	15	155	54.25	16
g6	16	155	54.25	10.52
g7	23	310	108.5	10.52
g8	23	350	140	10.89
g9	7	350	75	20.7
g10	13	591	206.85	20.93
g11	15	60	12	26.11
g12	22	300	0	0

Table A2. Branch parameters for IEEE RTS 24-bus network (Source: [6])

From Bus	To Bus	Reactance [p.u.]	Capacity [MVA]	From Bus	To Bus	Reactance [p.u.]	Capacity [MVA]
1	2	0.0139	175	11	13	0.0476	500
1	3	0.2112	175	11	14	0.0418	500
1	5	0.0845	175	12	13	0.0476	500
2	4	0.1267	175	12	23	0.0966	500
2	6	0.192	175	13	23	0.0865	500
3	9	0.119	175	14	16	0.0389	500
3	24	0.0839	400	15	16	0.0173	500
4	9	0.1037	175	15	21	0.0245	1000
5	10	0.0883	175	15	24	0.0519	500
6	10	0.0605	175	16	17	0.0259	500
7	8	0.0614	175	16	19	0.0231	500
8	9	0.1651	175	17	18	0.0144	500
8	10	0.1651	175	17	22	0.1053	500
9	11	0.0839	400	18	21	0.013	1000
9	12	0.0839	400	19	20	0.0198	1000
10	11	0.0839	400	20	23	0.0108	1000
10	12	0.0839	400	21	22	0.0678	500

Table A3. Load parameters for IEEE RTS 24-bus network [6].

Bus	Load [MW]	Bus	Load [MW]
1	108	10	195
2	97	13	265
3	180	14	194
4	74	15	317
5	71	16	100
6	136	18	333
7	125	19	181
8	171	20	128
9	175		

Table A4. Reactances and lengths values used for REMix-MISO

From Bus	To Bus	Reactance [p.u.]	Reactance [Ω]	Length [km]	From Bus	To Bus	Reactance [p.u.]	Reactance [Ω]	Length [km]
1	2	0.01	2.65	0.26	11	13	0.05	9.06	0.91
1	3	0.21	40.22	4.02	11	14	0.04	7.96	0.80
1	5	0.08	16.09	1.61	12	13	0.05	9.06	0.91
2	4	0.13	24.13	2.41	12	23	0.10	18.40	1.84
2	6	0.19	36.56	3.66	13	23	0.09	16.47	1.65
3	9	0.12	22.66	2.27	14	16	0.04	7.41	0.74
3	24	0.08	15.98	1.60	15	16	0.02	3.29	0.33
4	9	0.10	19.75	1.97	15	21	0.02	4.67	0.47
5	10	0.09	16.82	1.68	15	24	0.05	9.88	0.99
6	10	0.06	11.52	1.15	16	17	0.03	4.93	0.49
7	8	0.06	11.69	1.17	16	19	0.02	4.40	0.44
8	9	0.17	31.44	3.14	17	18	0.01	2.74	0.27
8	10	0.17	31.44	3.14	17	22	0.11	20.05	2.01
9	11	0.08	15.98	1.60	18	21	0.01	2.47	0.25
9	12	0.08	15.98	1.60	19	20	0.02	3.77	0.38
10	11	0.08	15.98	1.60	20	23	0.01	2.06	0.21
10	12	0.08	15.98	1.60	21	22	0.07	12.91	1.29

7 Bibliography

[1] Federal Ministry for Economic Affairs and Energy, *Grid expansion: Grid expansion is an indispensable part of the energy transition.* [Online]. Available: https://www.bmwi.de/Redaktion/EN/Artikel/Energy/electricity-grids-of-the-future-02.html

[2] Netz Entwicklungs Plan Strom, *Transmission Sytem Operators: The Energiewende - new challenges for the energy infrastructure.* [Online]. Available: https://www.netzentwicklungsplan.de/en/background/transmission-system-operators (accessed: Dec. 2 2021).

[3] H. Zhang, V. Vittal, G. T. Heydt, and J. Quintero, "A Mixed-Integer Linear Programming Approach for Multi-Stage Security-Constrained Transmission Expansion Planning," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 1125–1133, 2012, doi: 10.1109/TPWRS.2011.2178000.

[4] M. Majidi-Qadikolai and R. Baldick, "Integration of Contingency Analysis With Systematic Transmission Capacity Expansion Planning: ERCOT Case Study," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 2234–2245, 2016, doi: 10.1109/TPWRS.2015.2443101.

[5] A. Wood, B. Wollenberg, and G. Sheblé, *Power Generation, Operation, and Control*, 3rd ed., 2014.

[6] A. Soroudi, *Power System Optimization Modeling in GAMS*. Cham: Springer International Publishing, 2017.

[7] J. Louda, "Optimization of the power network transfer capability for business purposes," University of West Bohemia, Pilsen, 2020.

[8] M. Mehrtash, A. Mohammadi, M. Barati, and A. Kargarian, "Security-Constrained Transmission Expansion Planning with Risk Index of N-1 Security Obtained from PMU Data," in *Security-Constrained Transmission Expansion Planning with Risk Index of N-1 Security Obtained from PMU Data*, Portland, OR, Aug. 2018 - Aug. 2018, pp. 1–5.

[9] I. de J. Silva, M. J. Rider, R. Romero, A. V. Garcia, and C. A. Murari, "Transmission network expansion planning with security constraints," *IEE Proc., Gener. Transm. Distrib.*, vol. 152, no. 6, p. 828, 2005, doi: 10.1049/ip-gtd:20045217.

[10] DLR Institute of Engineering Thermodynamics, *DLR Energy System Model REMix short description 2016.* [Online]. Available: https://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/Modellbeschreibungen/DLR_Energy_System_Model_REMix_short_description_2016.pdf

[11] W. A. Bukhsh, "Islanding model for preventing wide-area blackouts and the issue of local solutions of the optimal power flow problem," The University of Edinburgh, 2014.

[12] J. Hörsch, H. Ronellenfitsch, D. Witthaut, and T. Brown, "Linear Optimal Power Flow Using Cycle Flows," *Electric Power Systems Research*, vol. 158, no. 3, pp. 126–135, 2018, doi: 10.1016/j.epsr.2017.12.034.

[13] D. van Hertem, Verboomen J., and Purchala K., "Usefulness of DC power flow for active power flow analysis with flow controlling devices," in *8th IEE International Conference on AC and DC Power Transmission (ACDC 2006),* London, UK, Mar. 2006, pp. 58–62.

[14] S. Chatzivasileiadis, "Lecture Notes on Optimal Power Flow (OPF)," Nov. 2018. [Online]. Available: http://arxiv.org/pdf/1811.00943v1

[15] S. E. G. Mohamed, A. Y. Mohamed, and Y.H. Abdelrahim, "Power System Contingency Analysis to detect Network Weaknesses," 2012. [Online]. Available: https://www.researchgate.net/profile/salah-eldeen-gasim-mohamed/publication/260330850_power_system_contingency_analysis_to_detect_network_weaknesses

[16] R. Singh and L. Srivastava, "Line flow contingency selection and ranking using cascade neural network," *Neurocomputing*, vol. 70, 16-18, pp. 2645–2650, 2007, doi: 10.1016/j.neucom.2005.11.024.

[17] V. Brandwajn, "Efficient bounding method for linear contingency analysis," *IEEE Trans. Power Syst.*, vol. 3, no. 1, pp. 38–43, 1988, doi: 10.1109/59.43179.

[18] P. Sekhar and S. Mohanty, "Power system contingency ranking using Newton Raphson load flow method," in *2013 annual IEEE India conference (INDICON 2013): Mumbai, India, 13 - 15 December 2013*, Mumbai, India, 2013, pp. 1–4.

[19] G. K. Stefopoulos, F. Yang, G. J. Cokkinides, and A. P. Sakis Meliopoulos, "Advanced contingency selection methodology," in *Proceedings / 37th North American Power Symposium: October 23 - 25, 2005, Iowa State University, Ames, Iowa, USA*, Ames, IA, USA, 2005, pp. 67–73.

[20] A. Ozdemir and C. Singh, “Fuzzy Decision Making against Masking Problem in MW Contingency Ranking,” *IEEE Power Eng. Rev.*, vol. 22, no. 2, pp. 55–56, 2002, doi: 10.1109/MPER.2002.4311978.

[21] S. Ghosh and B. H. Chowdhury, “Design of an artificial neural network for fast line flow contingency ranking,” *International Journal of Electrical Power & Energy Systems*, vol. 18, no. 5, pp. 271–277, 1996, doi: 10.1016/0142-0615(94)00021-2.

[22] M. Pandit, L. Srivastava, and J. Sharma, “Cascade fuzzy neural network based voltage contingency screening and ranking,” *Electric Power Systems Research*, vol. 67, no. 2, pp. 143–152, 2003, doi: 10.1016/S0378-7796(03)00085-3.

[23] V. Brandwajn and M. G. Lauby, “Complete bounding method for AC contingency screening,” *IEEE Trans. Power Syst.*, vol. 4, no. 2, pp. 724–729, 1989, doi: 10.1109/59.193806.

[24] C. S. Song, C. H. Park, M. Yoon, and G. Jang, “Implementation of PTDFs and LODFs for Power System Security,” *Journal of International Council on Electrical Engineering*, vol. 1, no. 1, pp. 49–53, 2011, doi: 10.5370/JICEE.2011.1.1.049.

[25] J. Guo, Y. Fu, Z. Li, and M. Shahidehpour, “Direct Calculation of Line Outage Distribution Factors,” *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1633–1634, 2009, doi: 10.1109/TPWRS.2009.2023273.

[26] A. J. Conejo, L. Baringo Morales, S. J. Kazempour, and A. S. Siddiqui, *Investment in Electricity Generation and Transmission*. Cham: Springer International Publishing, 2016.

[27] M. Oloomi, “Transmission Expansion Planning in Deregulated Power Systems,” Technischen Universität Darmstadt, Germany, 2004.

[28] S. S. Torbaghan and M. Gibescu, “Optimum Transmission System Expansion Offshore Considering Renewable Energy Sources,” in *Optimization in Renewable Energy Systems*: Elsevier, 2017, pp. 177–231.

[29] R. Villasana, L. Garver, and S. Salon, “Transmission Network Planning Using Linear Programming,” *IEEE Trans. on Power Apparatus and Syst.*, PAS-104, no. 2, pp. 349–356, 1985, doi: 10.1109/TPAS.1985.319049.

[30] N. Alguacil, A. L. Motto, and A. J. Conejo, “Transmission expansion planning: a mixed-integer LP approach,” *IEEE Trans. Power Syst.*, vol. 18, no. 3, pp. 1070–1077, 2003, doi: 10.1109/TPWRS.2003.814891.

[31] M. J. Rider, A. V. Garcia, and R. Romero, “Power system transmission network expansion planning using AC model,” *IET Gener. Transm. Distrib.*, vol. 1, no. 5, p. 731, 2007, doi: 10.1049/iet-gtd:20060465.

[32] L. Bahiense, G. C. Oliveira, M. Pereira, and S. Granville, “A mixed integer disjunctive model for transmission network expansion,” *IEEE Trans. Power Syst.*, vol. 16, no. 3, pp. 560–565, 2001, doi: 10.1109/59.932295.

[33] M. Jenabi, S. M. T. Fatemi Ghomi, and Y. Smeers, “Bi-Level Game Approaches for Coordination of Generation and Transmission Expansion Planning Within a Market Environment,” *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2639–2650, 2013, doi: 10.1109/TPWRS.2012.2236110.

[34] S. Binato, M. Pereira, and S. Granville, “A new Benders decomposition approach to solve power transmission network design problems,” *IEEE Trans. Power Syst.*, vol. 16, no. 2, pp. 235–240, 2001, doi: 10.1109/59.918292.

[35] J. Zhu, *Optimization of power system operation*. Piscataway N.J., Chichester: Wiley-IEEE; John Wiley [distributor], 2009.

[36] S. Hariharan, “Transmission Expansion Planning with Large Scale Renewable Resource Integration,” Arizona State University, 2012.

[37] A. H. Escobar, R. A. Gallego, and R. Romero, “Multistage and Coordinated Planning of the Expansion of Transmission Systems,” *IEEE Trans. Power Syst.*, vol. 19, no. 2, pp. 735–744, 2004, doi: 10.1109/TPWRS.2004.825920.

[38] C. Wang, “Transmission Network Expansion Planning using the Railway Network,” Karlsruhe Institute of Technology, 2017.

[39] Benoit Chachuat, *Mixed-Integer Linear Programming (MILP): Model Formulation.* [Online]. Available: http://macc.mcmaster.ca/maccfiles/chachuatnotes/07-MILP-I_handout.pdf

[40] GAMS, *General Algebraic Modeling System.* [Online]. Available: https://www.gams.com/

[41] DLR Energy System Analysis Modelling Group, *MISO General Concept.* [Online]. Available: https://miso.pages.gitlab.dlr.de/docs/about/general_concept.html

[42] N. Wulff, “REMix Tutorial – Part 2: The General Algebraic Modeling Language (GAMS) in a nutshell: Part 2.2 Advanced features and REMix design patterns,” DLR, Dec. 2020.

[43] DLR Energy System Analysis Modelling Group, *MISO Modules.* [Online]. Available: https://miso.pages.gitlab.dlr.de/docs/explanations/modules.html

[44] I. Kasikci, *Short circuits in power systems: A practical guide to IEC 609090*. Weinheim, Germany: Wiley-VCH, 2018. [Online]. Available: https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=5144711

[45] S. Lehnhoff, *Specialization Energy Informatics: Network Modelling III*.

[46] R. Villanasa, “Transmission network planning using linear and mixed linear integer programming: Ph.D. dissertation,” Ressenlaer Polythechnic Institute, 1984.

[47] A. K. Kazerooni and J. Mutale, “Transmission Network Planning Under Security and Environmental Constraints,” *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 1169–1178, 2010, doi: 10.1109/TPWRS.2009.2036800.

[48] J. Merino, P. Mendoza-Araya, and C. Veganzones, “State of the Art and Future Trends in Grid Codes Applicable to Isolated Electrical Systems,” *Energies*, vol. 7, no. 12, pp. 7936–7954, 2014, doi: 10.3390/en7127936.

[49] Federal Ministry for Economic Affairs and Energy (BMWi), “Electricity 2030: Long-term trends – tasks for the coming years,” 2017. [Online]. Available: https://www.bmwi.de/Redaktion/EN/Publikationen/electricity-2030-concluding-paper.pdf?__blob=publicationFile&v=9