Pontifícia Universidade Católica
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Raphael Augusto Proença Rosa Saavedra

Co-Optimizing Post-Contingency Transmission Switching in Power System Operation Planning

Dissertação de Mestrado

Dissertation presented to the Programa de Pós-Graduação em Engenharia Elétrica of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Engenharia Elétrica.

Advisor: Prof. Alexandre Street de Aguiar

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Prof. Alexandre Street de Aguiar
Advisor
Departamento de Engenharia Elétrica – PUC-Rio

Prof. Davi Michel Valladão
Departamento de Engenharia Industrial – PUC-Rio

Prof. José Manuel Arroyo
Universidad de Castilla – La Mancha

Rio de Janeiro, September 18th, 2019

Raphael Augusto Proença Rosa Saavedra

Raphael Augusto Proença Rosa Saavedra received his B.Sc. degree in Electrical Engineering in 2017 from the Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Brazil. During his undergraduate program, he spent a year as an exchange student at the University of Maryland, College Park, and was also a research intern at the Illinois Institute of Technology in Chicago. Since 2014, he has been actively participating in research projects at the Laboratory of Applied Mathematical Programming and Statistics (LAMPS) in the Department of Electrical Engineering at PUC-Rio.

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Abstract

Proença Rosa Saavedra, Raphael Augusto; Street de Aguiar, Alexandre (Advisor). **Co-Optimizing Post-Contingency Transmission Switching in Power System Operation Planning**. Rio de Janeiro, 2019. 71p. Dissertação de Mestrado – Departamento de Engenharia Elétrica, Pontifícia Universidade Católica do Rio de Janeiro.

Transmission switching has been previously shown to offer significant benefits to power system operation, such as cost savings and reliability enhancements. Within the context of co-optimized electricity markets for energy and reserves, this work addresses the co-optimization of post-contingency transmission switching in power system operation planning. The proposed models for unit commitment and economic dispatch differ from existing formulations due to the joint consideration of three major complicating factors. First, transmission switching actions are considered both in the pre- and post-contingency states, thereby requiring binary post-contingency variables. Secondly, generation scheduling and transmission switching actions are co-optimized. In addition, the time-coupled operation of generating units is precisely characterized. The proposed models are formulated as challenging mixed-integer programs for which the off-the-shelf software customarily used for simpler models may lead to intractability even for moderately-sized instances. As a solution methodology, we present enhanced versions of an exact nested column-and-constraint generation algorithm featuring the inclusion of valid constraints to improve the overall computational performance. Numerical simulations demonstrate the effective performance of the proposed approach as well as its economic and operational advantages over existing models disregarding post-contingency transmission switching.

Keywords

Post-Contingency Transmission Switching; Unit Commitment; Economic Dispatch; Adjustable Robust Optimization; Nested Column-and-Constraint Generation Algorithm.

Resumo

Proença Rosa Saavedra, Raphael Augusto; Street de Aguiar, Alexandre. **Co-Otimizando Transmission Switching Pós-Contingência no Planejamento da Operação de Sistemas de Potência**. Rio de Janeiro, 2019. 71p. Dissertação de Mestrado – Departamento de Engenharia Elétrica, Pontifícia Universidade Católica do Rio de Janeiro.

Transmission switching já foi apresentado anteriormente como uma ferramenta capaz de prover benefícios significativos na operação de sistemas de potência, como redução de custos e aumento de confiabilidade. Dentro do contexto de mercados co-otimizados para energia e reservas, este trabalho endereça a co-otimização de transmission switching pós-contingência no planejamento da operação de sistemas elétricos. Os modelos propostos para programação diária e despacho econômico diferem de formulações existentes devido à consideração conjunta de três fatores complicadores. Primeiro, ações de transmission switching são consideradas nos estados pré e pós-contingência, portanto requerendo variáveis binárias pós-contingência. Adicionalmente, a programação de geradores e as ações de transmission switching são co-otimizadas. Além disso, a operação de geradores é caracterizada temporalmente em um contexto multi-período. Os modelos propostos são formulados como programas inteiros-mistos desafiadores para os quais os softwares comerciais comumente utilizados para modelos mais simples podem levar à intratabilidade até para instâncias de tamanho moderado. Como metodologia de solução, nós apresentamos uma versão aperfeiçoada de um algoritmo de geração de colunas e restrições aninhado, com a adição de restrições válidas para melhorar o desempenho computacional. Simulações numéricas demonstram o desempenho efetivo da abordagem proposta, assim como suas vantagens econômicas e operacionais sobre modelos existentes que desconsideram o transmission switching pós-contingência.

Palavras-chave

Transmission Switching Pós-Contingência; Programação Diária; Despacho Econômico; Otimização Robusta Ajustável; Algoritmo de Geração de Colunas e Restrições Aninhado.

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1
Introduction

The operation of power systems is deeply rooted in mathematical optimization. As system operators and planners seek optimal operation schedules, the problems faced by these agents give rise to mathematical programs aimed at deriving solutions that can offer directions and useful insights for practical implementation. A common objective among agents is to meet the demands on each of the multiple buses of the system at minimum cost. To that end, it is necessary to incorporate in the models the dispatch of generators, the power flows, and the related electrical and operational constraints. Moreover, in addition to supplying demand, system operators and planners also have to take into account the effects of contingencies and load fluctuations. This is necessary in order to protect the system from potential power imbalance scenarios. Such protection is achieved by co-optimizing energy with ancillary services such as reserves and ramping [1]. In the literature, these problems are addressed within deterministic, stochastic, and robust frameworks [2–4].

Assuring the reliability of a power system is one of the main goals sought in the problems presented in this work. The North American Electric Reliability Corporation (NERC) defines reliability as "the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components" [5]. The mentioned disturbances and loss of components can occur due to sudden load fluctuations, accidental outages (caused by the environment, by the malfunction of machinery, etc.), or deliberate attacks (see [6] and Chapter 14 of [7]). Nonetheless, it is of paramount importance that power systems be prepared against credible outages, as power imbalance scenarios can lead to substantial economic damage.

Both in the industry and the literature, power system operation models customarily aim to guarantee reliability by enforcing certain deterministic security criteria. For example, an $n-1$ criterion considers the outage of any single system component, i.e., any generator or transmission line. More generally, an $n-K$ criterion considers the outage of any K components simultaneously, while an $n-K^G-K^L$ criterion considers the outage of any K^G generators and any K^L lines simultaneously [8–10]. Naturally, conservative security criteria usually lead to more expensive operation schedules. On the other hand, these criteria allow obtaining a more robust and resilient operation with respect to the occurrence of contingencies and load fluctuations.

Among the problems faced by system operators and planners, in this work we focus on *unit commitment* and *economic dispatch*. These problems act in the two major stages of power system operation: the day-ahead setting and the real-time setting. More specifically, we study the *contingency-constrained* versions of these problems, i.e., formulations wherein the system operation under each credible contingency state according to a prescribed security criterion is explicitly considered. Contingency-constrained formulations tend to be more challenging, as they require the precise modeling of the energy redispatch under each contingency state. Conversely, they are arguably more accurate with respect to the real-world operation since, by characterizing the operation under each credible contingency state, reserve deliverability is guaranteed [11].

Unit commitment (UC) is one of the main tools used by power system operators to manage energy resources one day ahead. In the day-ahead setting, UC represents an operation planning problem that is aimed at the co-optimization of generation scheduling and ancillary services for the following day. The goal of this optimization problem is to schedule and dispatch generators to meet future demand with minimum operating costs [2–4]. Such scheduling comprises mainly the on/off status of each generator in each time period, but must also take into account the power output of generators as well as the power flows in the transmission lines. Additionally, system operators must co-optimize energy with ancillary services to minimize the risks imposed by contingencies, load fluctuations and other sources of uncertainty. UC represents a challenging problem due to the large number of binary variables arising from the need to model the on/off statuses of each generator in each time period for the considered time frame, which is generally 24 hours.

While it has been shown that other formulations can lead to suboptimal or infeasible solutions once contingencies occur [11], contingency-constrained unit commitment (CCUC) [8, 9, 12–16] ensures reserve deliverability under every contingency considered in the formulation. Furthermore, CCUC provides a suitable modeling framework for considering tight security criteria. Within this context, an $n-K$ criterion was first accounted for in the CCUC model proposed in [8], and was extended in [12] by including network constraints and transmission line contingencies. In [9], an adjustable robust optimization model was proposed, wherein the worst-case contingency is found for any given pre-contingency schedule and the best corrective actions are determined to minimize the system power imbalance. Recent works also use robust formulations to take into account renewable generation uncertainty, fast-acting units, and other practical aspects [13–16].

The economic dispatch (ED) problem represents the short-term determination of the optimal energy dispatch for each generator subject to transmission and operational constraints [17]. Contrary to UC, which takes place in a day-ahead context and comprises the scheduling of generators, ED deals with the short-term dispatch of generators when their on/off statuses have already been decided. On the one hand, general ED formulations represent a simpler model when compared to UC due to the non-consideration of the on/off statuses of generators. On the other hand, since ED is conducted in a short-term setting, it must be run within a narrower time frame. Nonetheless, modern methodologies allow the consideration of significant renewable generation [18, 19], security-constrained formulations [20], among other complicating factors. In terms of solution methodologies, ED has been addressed in the literature using mathematical optimization [21, 22], genetic algorithms [23, 24], and metaheuristics such as particle swarm optimization [25, 26] and simulated annealing [27, 28].

Both in the day-ahead scheduling of generators and in the short-term determination of the optimal economic dispatch, ancillary services are crucial to secure operation feasibility and to curtail the risk of possible power imbalance scenarios. Notwithstanding the importance of generation ancillary services such as reserves and ramping, the consideration of a flexible network topology can also produce significant benefits to power system operation. In this context, transmission switching, also known as topology control, represents an operational feature whereby transmission lines can be switched on and off by the system operator in each time period [29, 30]. While transmission switching has been extensively studied in the literature of power system operation, the vast majority of the works have considered exclusively pre-contingency switching actions, which are taken before any uncertainty occurs.

In this work, we explore transmission switching as a potentially powerful ancillary service that can act both in preventive and real-time reactive fashion within multi-period contingency-constrained unit commitment and economic dispatch formulations. We show that the inclusion of co-optimized post-contingency switching provides significant benefits to power system operation, such as substantial cost savings and decreases in worst-case power imbalance levels. Finally, we study the effects of the co-optimization of post-contingency switching in the pre-contingency scheduling of reserves and line statuses.

To that end, we propose novel formulations that ensure such a co-optimization over a multi-period setting with inter-temporal constraints. We devise a solution methodology based on an exact decomposition algorithm to tackle the challenging mathematical programs that arise from the proposed formulations. Finally, numerical simulations are conducted based on a small illustrative system and on the IEEE 118-bus system [31], which acts as a medium-scale benchmark, and relevant conclusions are drawn.

1.1 Contributions

The main contributions of this work are:

1. Novel formulations for the contingency-constrained unit commitment and economic dispatch problems are proposed. As a salient feature, pre- and post-contingency transmission switching are co-optimizated with energy and reserves over a multi-period setting with inter-temporal constraints. The proposed monolithic formulations are then recast as adjustable robust optimization problems with trilevel min-max-min structures.

2. Decomposition methodologies based on the nested column-and-constraint generation algorithm [32] are proposed for both problems and shown to greatly outperform the direct application of off-the-shelf commercial solvers to the monolithic formulation. Furthermore, the nested column-and-constraint generation algorithm is enhanced with the addition of valid constraints, reducing both the computing times and the number of necessary iterations to attain convergence.

3. A study of the benefits of co-optimized pre- and post-contingency transmission switching is presented in numerical simulations based on an illustrative 4-bus system and on the IEEE 118-bus system. The models considering both pre- and post-contingency switching are compared to models considering no switching and only pre-contingency switching. The results illustrate the potential reductions in costs, levels of power imbalance, and changes in line statuses. For the 118-bus system, cost savings of up to 28% are attained and potential power imbalance levels are completely nullified. Furthermore, it is shown that the co-optimization of post-contingency switching allows unlocking reserve capabilities that would otherwise be constricted due to electrical constraints.

1.2 Outline

The remainder of this work is organized as follows. Chapter 2 presents transmission switching as a relevant operational feature, provides a brief review of the related literature, and discusses pre- *versus* post-contingency transmission switching. In Chapter 3, the adjustable robust optimization framework utilized in both problems addressed in this work is presented. Chapter 4 presents the nested column-and-constraint generation algorithm, which represents the basis of the solution methodology employed in this work. Chapters 5 and 6 present the formulations for the contingency-constrained unit commitment and economic dispatch with co-optimized pre- and post-contingency transmission switching, respectively, as well as the solution methodologies utilized and numerical results. Relevant conclusions are drawn in Chapter 7. Finally, the nomenclature utilized in the formulations in Chapter 5 and 6 is provided in Appendix A.

2
Transmission Switching

Transmission switching (TS) or topology control represents the deliberate switching of the on/off status of a transmission line by the operator. Although the idea of switching off a functioning transmission line might seem odd at first, it has been shown to potentially provide significant operating cost reductions and system reliability enhancements. This result stems from Kirchhoff's voltage law, which has to be met for every loop in the system, i.e., every loop in the system represents an additional electrical constraint that can potentially curb certain reserve and ramping capabilities. Thus, by switching off one or more specific transmission lines, loops can be removed, resulting in a less constrained system operation. The end result of this operational feature is that additional reserve capabilities may be unlocked, which might be crucial to guarantee system reliability during high load periods.

Figs. 2.1–2.3 illustrate how TS can benefit a power system that is under stress due to a contingency. In Fig. 2.1, an example of a 5-bus system that has two main areas connected by two transmission lines is provided. It can be seen that, under normal conditions, both areas are completely self-sufficient. However, as depicted in Fig. 2.2, if a contingency suddenly occurs in one line of the second area, the consequence is a power imbalance of 20 MW in one of the buses. Note that, even though such a power imbalance is present, generator 1 is not outputting its full capacity due to a constraint imposed by Kirchhoff's voltage law. In fact, generator 1 would be capable of injecting an additional 20 MW into the network, which would nullify the current power imbalance, if not for the constriction imposed on the system by the loop comprising lines 1, 2, and 3. Nonetheless, as depicted in Fig. 2.3, it is possible to address this issue by switching off line 2, thus removing the aforementioned loop from the system and unlocking the full generating capability of generator 1.

TS has been broadly studied in the power system literature, including within the context of contingency analysis, UC, ED, optimal power flow, and expansion planning. In [29], Fisher *et al.* presented a generation dispatch model with TS that resulted in significant cost savings, which constituted the first step to motivate further studies involving TS in power system operation. The model described in [29] was then extended in [30] with the

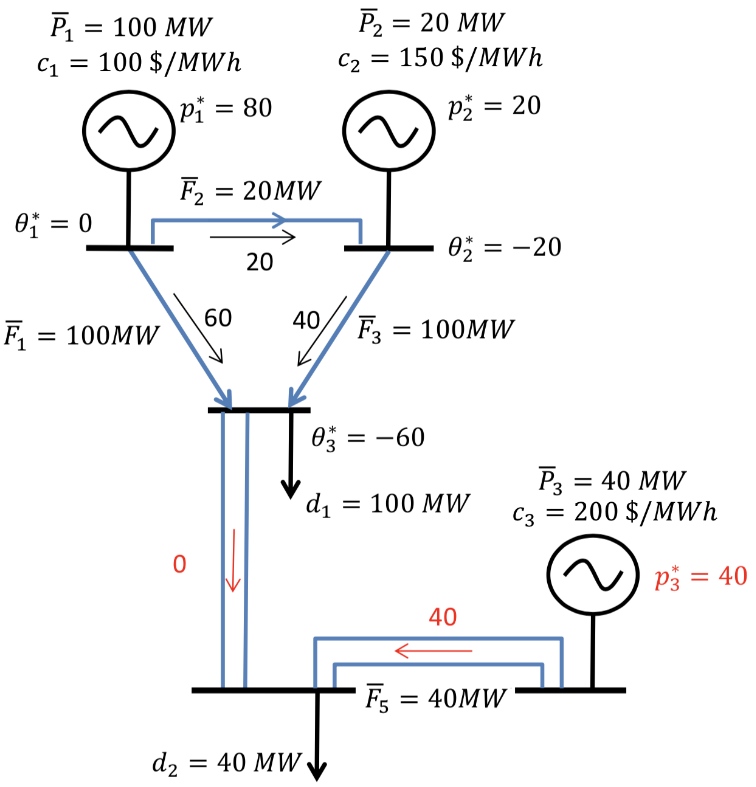

Figure 2.1: Operation of an illustrative 5-bus system under the normal state.

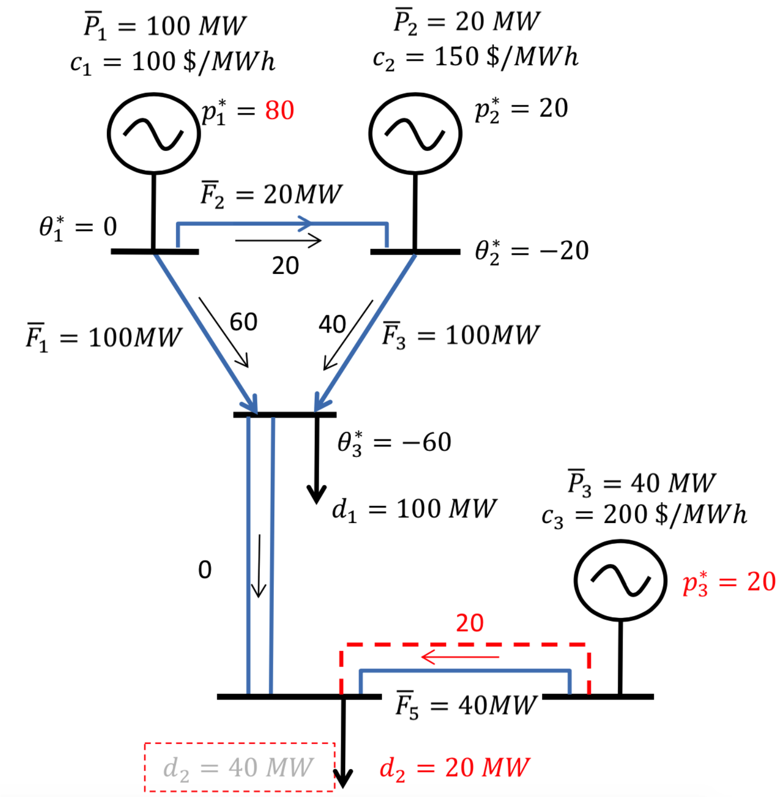

Figure 2.2: A contingency occurs in one of the lines, resulting in a power imbalance of 20 MW.

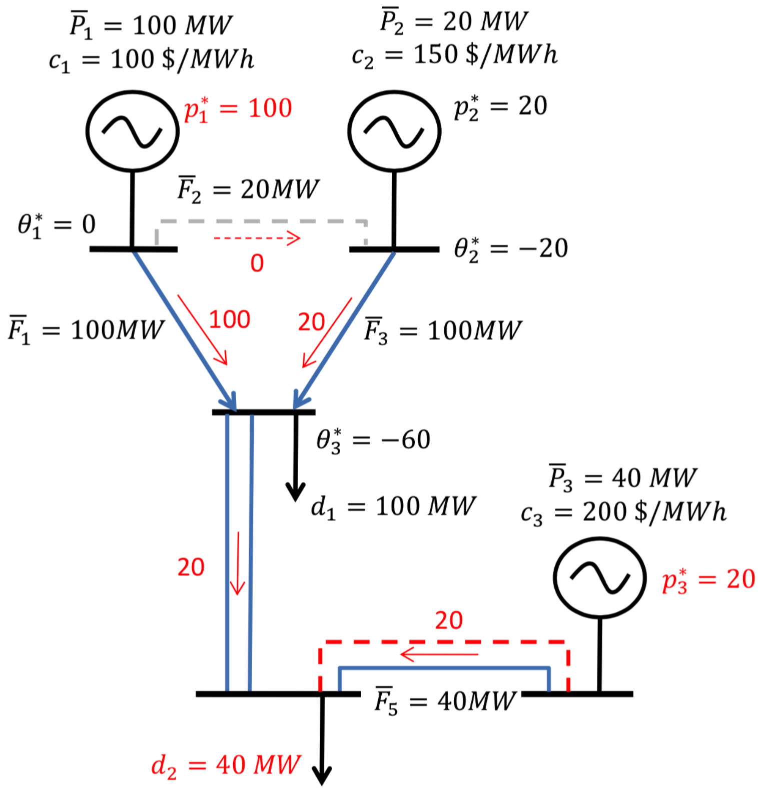

Figure 2.3: By switching off line 2, the operator allows generator 1 to output its maximum capacity, thus avoiding the power imbalance.

consideration of contingencies under an $n-1$ security criterion. Ever since, in the related literature, several works utilizing security-constrained, contingency-constrained, and related formulations have considered TS actions [33–42]. However, the vast majority of these works consider only pre-contingency TS actions, whereby topology changes are allowed in the normal state or base case, i.e., before uncertainty unfolds. We present in this chapter a brief review of these works.

In Hedman's notable work [33], pre-contingency TS was first brought to the CCUC framework in day-ahead electricity markets. Moreover, [33] represented the first effort to effectively co-optimize TS with energy and reserve scheduling. However, the computational effort required to perform such a co-optimization was deemed impractical and heuristics were proposed to address the problem. In [34], a sequential and hence inexact approach was proposed to incorporate pre-contingency TS into the multi-period security-constrained UC. The same authors developed a similar methodology in [35] to address generation and transmission expansion planning with TS. While the decomposition methodologies proposed in [34] and [35] allowed addressing larger instances than previous works, the sequential approaches utilized lead to non-co-optimized, thus suboptimal, schedules. In [36], an adjustable robust optimization framework was utilized to co-optimize pre-contingency TS with generation scheduling over a single-period setting while considering corrective redispatch actions. While the proposed model represented a methodological advance from previous works, the limitations of a single-period formulation preclude its application in a practical, real-world setting. Finally, in [37], an adjustable robust optimization framework was employed in energy storage expansion planning considering TS and wind farms.

Notwithstanding the relevance of the aforementioned works, they all share an important limitation by only considering TS actions before the uncertainty is observed. The distinction between pre- and post-contingency TS [38, 42, 43] brings a new light to this class of problems. In a two-stage optimization setting [44], widely used in the power system literature, we define *pre-contingency* or *preventive* TS as the set of TS actions taken before the uncertainty is observed, which may represent load uncertainty, renewable generation, or contingencies. Conversely, *post-contingency*, *reactive*, or *corrective* TS is defined as the set of TS actions taken after the uncertainty is observed. The majority of the TS literature has hitherto utilized formulations considering only pre-contingency TS actions, which have been repeatedly shown to potentially reduce operational costs and improve system reliability. On the other hand, recent work on unit commitment has presented post-contingency TS as a powerful tool to alleviate power imbalance levels caused by contingencies [38, 42].

In fact, independent system operators and regional transmission organizations such as PJM already utilize post-contingency TS in practice [45]. However, the employment of such an operational feature, if not considered in the pre-uncertainty stage, leads to inconsistencies between planning and operation, resulting in suboptimal scheduling [46]. In this work, we show that the co-optimization of post-contingency TS leads to significantly different pre-contingency line scheduling, as opposed to sequential approaches wherein the pre-contingency schedule is not affected by possible corrective switching actions. The difference between sequential and co-optimized approaches for UC is illustrated in Figs. 2.4 and 2.5.

The significance of post-contingency TS has also been discussed in [39–41, 45, 47–49], among others. In [40, 41, 47, 48], the benefits of post-contingency TS were examined within the context of real-time contingency analysis. An optimal power flow with post-contingency TS was proposed in [39]. However, a sequential approach was employed wherein corrective TS actions are not co-optimized, thus not affecting the pre-uncertainty stage. In [49], corrective TS was incorporated in a stochastic UC model without considering

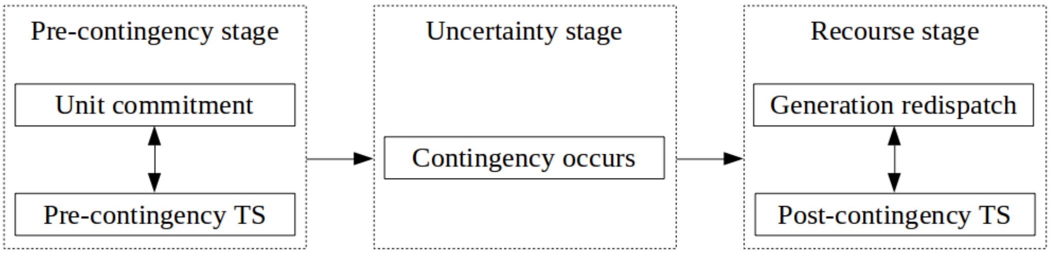

Figure 2.4: Flowchart exemplifying sequential approach.

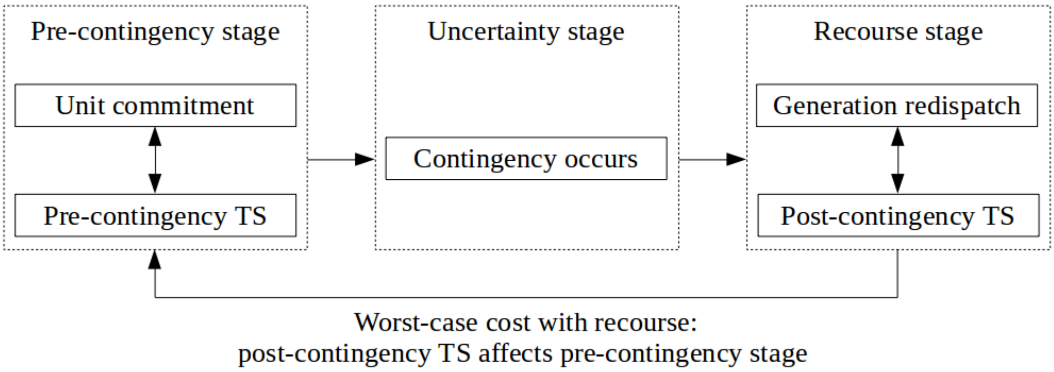

Figure 2.5: Flowchart exemplifying co-optimized approach.

contingencies or co-optimizing reserve offers. However, despite the practical advantages of corrective switching, little attention has been paid to the co-optimization of post-contingency TS with energy and reserves, being [38] the only relevant exception.

In [38], post-contingency TS was co-optimized with energy and reserve offers for the first time in the literature. For that purpose, a single-period contingency-dependent model was devised wherein system operation was explicitly characterized for all possible contingencies. However, such a formulation represents a computationally challenging problem, and the straightforward application of off-the-shelf state-of-the-art software as proposed in [38] leads to intractability for instances considering a practical multi-period setting even for moderately-sized systems. Although works such as [36] and [38] have presented single-period formulations, such a simplification is not adequate for practical implementation since it disregards relevant operational factors such as inter-temporal constraints. Moreover, the non-consideration of a multi-period setting may lead to a significantly suboptimal operation, as future time periods can affect the decisions that must be made now, and in the case of a single-period model, that information is beyond the scheduling horizon and thus will not be utilized [50].

Approach	Pre-contingency TS	Post-contingency TS	Co-optimization of generation scheduling and TS	Multi-period setting	Decomposition methodology
Hedman *et al.* (2010) [33]	✓	–	✓	✓	–
Khodaei and Shahidehpour (2010) [34]	✓	–	–	✓	✓
Ayala and Street (2014) [38]	✓	✓	✓	–	–
Ding and Zhao (2016) [36]	✓	–	✓	–	✓
Proposed approach	✓	✓	✓	✓	✓

Table 2.1: Proposed Approach Versus the Related Literature

Therefore, new techniques are yet needed to address the co-optimization of energy, reserves, and post-contingency TS actions in multi-period power system operation models, including unit commitment and economic dispatch. Additionally, the effects of the co-optimization of post-contingency TS in the scheduling of generation, reserves, and line statuses still need further investigation. In this work, we extend the state-of-the-art works on CCUC with TS [33, 34, 36, 38] from both a modeling and a methodological perspective, as summarized in Table 2. In this table, symbols "✓" and "–" indicate whether a particular aspect is considered or not.

On the modeling side, both pre- and post-contingency TS actions are jointly considered, unlike [33,34,36]. It should also be noted that, in contrast to the sequential approach of [34], TS and generation scheduling are co-optimized, i.e., the pre-contingency stage explicitly takes into account the best network reaction with post-contingency TS. Moreover, the proposed model departs from the only available CCUC formulation considering post-contingency TS [38] by precisely considering the effect of TS on a multi-period setting with inter-temporal operational constraints, such as ramping limits, start-up and shutdown costs, and minimum up and down times, which were also neglected in [36]. As a result, the proposed models provide the optimal energy and reserve scheduling policy considering both preventive and corrective transmission flexibility.

From a methodological perspective, the proposed approach also differs significantly from the related literature [33, 34, 36, 38]. Due to its dimension, the resulting mixed-integer program is unsuitable for the direct application of off-the-shelf commercial solvers relying on state-of-the-art branch-and-cut algorithms, as done in [33] and [38]. Furthermore, the use of binary variables for post-contingency TS actions precludes the application of either the method adopted in [34], which is based on Benders decomposition [51], or the column-and-constraint generation algorithm (CCGA) [52] utilized in [36]. As an alternative to the methods employed in [33, 34, 36] and [38], we use an exact master-subproblem decomposition technique consisting in an enhanced version of the nested CCGA. The standard nested CCGA [32] has been successfully applied to address other UC models wherein binary recourse actions were related to the operation of energy storage [53] and fast-acting units [54]. The proposed solution approach exploits the countability of the set of possible post-contingency TS actions to devise an additional inner loop. The nested CCGA framework is presented in Chapter 4.

3
Adjustable Robust Optimization Framework

Robust optimization [55–57] is a framework which was first proposed in [58] that deals with uncertainty through the definition of an *uncertainty set*. Its goal is to derive a solution that is optimal under the worst case among those contemplated in the defined uncertainty set. This can be achieved with the following program:

$$\underset{\mathbf{y}}{\text{minimize}} \quad \mathbf{h}(\mathbf{y}, \mathbf{u}) \tag{3-1}$$

$$\text{subject to} \quad \mathbf{f}(\mathbf{y}, \mathbf{u}) \leq \mathbf{0}, \quad \forall \mathbf{u} \in \mathcal{U} \tag{3-2}$$

In this case, we are minimizing $\mathbf{h}(\mathbf{y}, \mathbf{u})$ subject to certain constraints for all possible values of $\mathbf{u}$ considered in the uncertainty set $\mathcal{U}$. This means constraints (3-2) need to be satisfied even in the worst possible realization of the uncertainty. For example, in a farming problem [59] where we are minimizing the production cost of a farmer and $\mathbf{u}$ represents the uncertain yield of several crops, problem (3-1)–(3-2) would find the solution that minimizes the production cost assuming that the yield of every single crop is the worst possible.

An interesting way to rewrite problem (3-1)–(3-2) is the following:

$$\min_{\mathbf{y} \in \mathcal{Y}} \max_{\mathbf{u} \in \mathcal{U}} \quad \mathbf{h}(\mathbf{y}, \mathbf{u}) \tag{3-3}$$

where we consider constraints (3-2) are represented in $\mathcal{Y}$. Perhaps the main difference from (3-1)–(3-2) is that $\mathbf{u}$ is now a decision variable instead of being on the right-hand side. This change is interesting from an implementational point-of-view, as the elements in the uncertainty set $\mathcal{U}$ do not need to be explicitly considered and therefore the complexity of solving problem 3-3 does not necessarily depend on the cardinality of $\mathcal{U}$, whereas considering $\mathbf{u}$ on the right-hand side as in (3-1)–(3-2) can result in a problem with up to infinite constraints. Furthermore, when compared to other approaches to address uncertainty such as stochastic optimization, not having to specify the joint probability distribution of the uncertainty is a relevant advantage.

Perhaps the most important modeling aspect within robust optimization is the definition of the uncertainty set. In the pioneer work by Soyster [58], a simple formulation was utilized wherein the uncertainty set assumed the form of a box, bounding all uncertain parameters within predefined upper and lower limits. Then, Ben-Tal and Nemirovski formalized the concepts of robust optimization and uncertainty sets in [55], while also providing relevant results for ellipsoidal uncertainty sets. Finally, in the seminal work by Bertsimas [57], an approach to improve the trade-off between robustness and conservatism was proposed. The approach involves the utilization of a polyhedral uncertainty set allied with a robustness parameter that is responsible for adjusting the level of conservatism as desired.

There are two aspects in formulation (3-1)–(3-2) that can be subjected to criticism. First, it is easy to see that it represents an overly conservative approach for most practical problems. Going back to the farming example, if we suppose that the farm produces five types of crops, it is highly unlikely that all five crops will have the worst possible yield simultaneously. This scenario becomes even more extreme if we suppose the farm has 20 types of crops instead. Secondly, formulation (3-1)–(3-2) does not consider the possibility of *recourse actions* that can be taken after the uncertainty is observed, which is a common feature among problems of this nature. In [57], the first issue was addressed through the robustness parameter, but the second issue remained.

In order to address this limitation, adjustable robust optimization (ARO) comes up as an alternative [44]. In the literature, ARO has also been called adaptive, adaptable or simply two-stage robust optimization. As its name suggests, ARO offers the possibility of adjustments in the face of uncertainty through a two-stage formulation. It has gained popularity in the recent years for applications where there is significant uncertainty but the related probability distribution is hard or costly to characterize [60–63]. ARO is often formulated with a trilevel min-max-min structure such as follows:

$$\min_{\mathbf{y}\in\mathcal{Y}} \max_{\mathbf{u}\in\mathcal{U}} \min_{\mathbf{x}\in\mathcal{F}(\mathbf{y},\mathbf{u})} \quad \mathbf{h}(\mathbf{y},\mathbf{u},\mathbf{x}) \tag{3-4}$$

In (3-4), vector $\mathbf{y}$ denotes the first-stage variables, $\mathbf{u}$ is a point in the uncertainty set $\mathcal{U}$, and vector $\mathbf{x}$ stands for the second-stage variables or recourse actions. The trilevel formulation is straightforward when it comes to characterizing the real-world problem: the upper level represents the “here and now” decisions, which must be taken before the uncertainty is observed; the middle level represents an oracle problem that finds the worst-case uncertainty realization with respect to the upper-level decisions; and the lower level represents the recourse actions that aim to minimize the damage caused by the worst-case uncertainty.

For example, within a power systems context, we can imagine the following formulation for contingency-constrained unit commitment, which will be further explored in Chapter 5:

$$
\begin{aligned}
& \text{minimize} && \textit{energy, reserve, and power imbalance costs} \\
& \text{subject to} && \textit{operational constraints} \\
& && \textit{worst-case contingency (WCC)} \\
WCC = \; & \text{maximize} && \textit{power imbalance (PI)} \\
& \text{subject to} && \textit{security criterion} \\
PI = \; & \text{minimize} && \textit{post-recourse power imbalance} \\
& \text{subject to} && \textit{operational constraints under WCC}
\end{aligned}
$$

Note that an interesting characteristic of this formulation is that its robustness does not come from any risk measure or conservatism parameter. Rather, it comes directly from the security criterion, which is what defines the uncertainty set. Therefore, there is a direct link between a well-known industry practice and the robustness present in this formulation.

Trilevel optimization models of the form (3-4) are oftentimes computationally challenging. In the literature, solution methodologies such as affine rules have been proposed [44], wherein the recourse decisions are assumed to take values according to affine functions of the uncertainty. However, decomposition methods with master-subproblem structures have eventually become the most popular and, in general, effective way to tackle ARO problems. The decomposition method that was first widely used to solve such problems is a master-subproblem method similar to Benders decomposition [51], with cutting planes being defined with dual information of the recourse problem [62–66]. The second method assumes the form of a column-and-constraint generation procedure and has been shown to outperform the Benders-like algorithms for robust unit commitment and robust transportation problems [52, 65].

In [52], a general column-and-constraint generation algorithm (CCGA) is defined to solve ARO problems. The main idea is to explore relaxations using a partial enumeration of the uncertainty set – given that $\mathcal{U}$ is a finite discrete set – in order to derive lower bounds for the original problem. Then, by gradually adding scenarios, tighter bounds are obtained. Therefore, the CCGA aims to create and gradually expand a subset of $\mathcal{U}$ by identifying significant scenarios at each iteration. However, as will be further described in Chapter 4, the CCGA is reliant on the dualization of the lower-level problem in order to derive a single-level subproblem formulation that comprises the middle- and lower-level problems. When the recourse problem is mixed-integer, this approach is no longer possible due to the presence of integer variables in the lower level. Considering post-contingency TS in power system operation results in such a case, as the on/off status of each transmission line is modeled by a binary variable.

In order to address this limitation, the *nested CCGA*, an extension of the standard CCGA which allows solving ARO problems with mixed-integer recourse, was proposed [32]. The nested CCGA tackles ARO problems with mixed-integer recourse by employing a standard CCGA procedure [52], which comprises a master-subproblem structure, and devising an *inner CCGA* to solve the subproblem. To that end, it is assumed that the set of discrete recourse decisions is bounded in order to exploit its countability. The nested CCGA framework is described in Chapter 4, while the solution methodology devised to solve the contingency-constrained unit commitment and economic dispatch problems with co-optimized post-contingency TS is presented in Chapters 5 and 6, respectively.

4
The Nested Column-and-Constraint Generation Algorithm

In this chapter, we present the nested CCGA first proposed in [32]. For the sake of consistency and readability, we utilize a compact notation similar to the one used in [32]. The nested CCGA tackles ARO problems with mixed-integer recourse by employing a standard CCGA procedure, which comprises a master-subproblem structure, and devising an *inner CCGA* to solve the subproblem.

Recall problem (3-4), written again here for convenience.

$$\min_{\mathbf{y}\in\mathcal{Y}} \max_{\mathbf{u}\in\mathcal{U}} \min_{\mathbf{x}\in\mathcal{F}(\mathbf{y},\mathbf{u})} \quad \mathbf{h}(\mathbf{y},\mathbf{u},\mathbf{x}) \tag{4-1}$$

We are interested in solving a particular case where the recourse problem is mixed-integer. This translates to a problem with the following form:

$$\min_{\mathbf{y}\in\mathcal{Y}} \ \mathbf{c}\mathbf{y} + \max_{\mathbf{u}\in\mathcal{U}} \min_{\mathbf{z},\mathbf{x}\in\mathcal{F}(\mathbf{y},\mathbf{u})} \quad \mathbf{d}\mathbf{x} + \mathbf{g}\mathbf{z} \tag{4-2}$$

where $\mathcal{Y} = \{\mathbf{y} \in \mathbb{R}^m_+ \times \mathbb{Z}^{m'}_+ : \mathbf{A}\mathbf{y} \geq \mathbf{b}\}$, $\mathcal{F}(\mathbf{y},\mathbf{u}) = \{(\mathbf{z},\mathbf{x}) \in \mathbb{Z}^n_+ \times \mathbb{R}^p_+ : \mathbf{E}\mathbf{x} + \mathbf{G}\mathbf{z} \geq \mathbf{f} - \mathbf{R}\mathbf{u} - \mathbf{D}\mathbf{y}, \mathbf{T}\mathbf{z} \geq \mathbf{v}\}$, and $\mathcal{U} = \{\mathbf{u} \in \mathbb{Z}^q_+ \times \mathbb{R}^{q'}_+ : \mathbf{H}\mathbf{u} \leq \mathbf{a}\}$. If we assume $\mathcal{U}$ is countable, i.e., $\mathcal{U} = \{\mathbf{u}^i\}_{i=1}^I$, then (4-2) can be rewritten as the following single-level mixed-integer problem:

$$\begin{aligned}
\underset{\mathbf{y},\mathbf{x},\Psi}{\text{minimize}} \quad & \mathbf{c}\mathbf{y} + \Psi \\
\text{subject to} \quad & \Psi \geq \mathbf{d}\mathbf{x}^i + \mathbf{g}\mathbf{z}^i; \quad \forall i = 1,\dots,I \\
& \mathbf{A}\mathbf{y} \geq \mathbf{b} \\
& \mathbf{E}\mathbf{x}^i + \mathbf{G}\mathbf{z}^i \geq \mathbf{f} - \mathbf{R}\mathbf{u}^i - \mathbf{D}\mathbf{y}; \quad \forall i = 1,\dots,I \\
& \mathbf{T}\mathbf{z}^i \geq \mathbf{v}; \quad \forall i = 1,\dots,I \\
& \mathbf{y} \in \mathbb{R}^m_+ \times \mathbb{Z}^{m'}_+, \mathbf{z}^i \in \mathbb{Z}^n_+, \mathbf{x}^i \in \mathbb{R}^p_+; \quad \forall i = 1,\dots,I
\end{aligned} \tag{4-3}$$

Although such a monolithic formulation is possible, it involves the explicit consideration of all the possible realizations in $\mathcal{U}$. Conversely, exploring a partial enumeration of the elements in $\mathcal{U}$ allows the derivation of bounds in iterative manner. First, consider the following problem, which represents the middle and lower levels of (4-2):

$$
\begin{aligned}
\mathbf{SP}: \quad \mathcal{Q}(\hat{\mathbf{y}}) = \max_{\mathbf{u}\in\mathcal{U}} \min_{\mathbf{z},\mathbf{x}} \quad & \mathbf{dx} + \mathbf{gz} \\
\text{subject to} \quad & \mathbf{Ex} + \mathbf{Gz} \geq \mathbf{f} - \mathbf{Ru} - \mathbf{D}\hat{\mathbf{y}} \\
& \mathbf{Tz} \geq \mathbf{v} \\
& \mathbf{z} \in \mathbb{Z}^n_+, \mathbf{x} \in \mathbb{R}^p_+
\end{aligned}
\tag{4-4}
$$

Note that **SP** derives an optimal scenario $\mathbf{u}^* \in \mathcal{U}$ that incurs the maximum cost in the objective function of the original problem (4-2), or a scenario for which the recourse problem is infeasible. If we suppose we are capable of solving **SP**, then the standard CCGA procedure can be successfully applied to problem (4-2). This procedure is presented next.

4.1
The Standard Column-and-Constraint Generation Algorithm

1. Initialize the lower and upper bounds as $LB = -\infty$, $UB = +\infty$, respectively, and the iteration counter as $k = 0$. Define a convergence tolerance ϵ^o.

2. Solve the master problem **MP**.

$$
\begin{aligned}
\mathbf{MP}: \quad \underset{\mathbf{y},\mathbf{x},\Psi}{\text{minimize}} \quad & \mathbf{cy} + \Psi \\
\text{subject to} \quad & \Psi \geq \mathbf{dx}^j + \mathbf{gz}^j; \quad \forall j = 1, \ldots, k \\
& \mathbf{Ay} \geq \mathbf{b} \\
& \mathbf{Ex}^j + \mathbf{Gz}^j \geq \mathbf{f} - \mathbf{Ru}^j - \mathbf{Dy}; \quad \forall j = 1, \ldots, k \\
& \mathbf{Tz}^j \geq \mathbf{v}; \quad \forall j = 1, \ldots, k \\
& \mathbf{y} \in \mathbb{R}^m_+ \times \mathbb{Z}^{m'}_+, \mathbf{z}^j \in \mathbb{Z}^n_+, \mathbf{x}^j \in \mathbb{R}^p_+; \quad \forall j = 1, \ldots, k
\end{aligned}
\tag{4-5}
$$

It is easy to see that **MP** is a relaxation of the original problem (4-3) where only a subset of k elements of $\mathcal{U}$ are considered. Therefore, the solution of **MP** yields a lower bound for (4-3).

3. Update lower bound using the solution of **MP**:

$$LB = \mathbf{cy}^* + \Psi^* \tag{4-6}$$

   If $UB - LB \leq \epsilon^o$, terminate.

4. Solve **SP** to obtain $\mathcal{Q}(\mathbf{y}^*)$ and $\mathbf{u}^*$.

5. Update upper bound using the solution of **SP**:

$$UB = \min\{UB, \mathbf{cy}^* + \mathcal{Q}(\mathbf{y}^*)\} \tag{4-7}$$

If $UB - LB \leq \epsilon^o$, terminate.

6. Add variables $(\mathbf{z}^{k+1}, \mathbf{x}^{k+1})$ and the following constraints to **MP**:

$$\begin{aligned}
&\Psi \geq \mathbf{dx}^{k+1} + \mathbf{gz}^{k+1} \\
&\mathbf{Ex}^{k+1} + \mathbf{Gz}^{k+1} \geq \mathbf{f} - \mathbf{Ru}^* - \mathbf{Dy} \\
&\mathbf{Tz}^{k+1} \geq \mathbf{v} \\
&\mathbf{z}^{k+1} \in \mathbb{Z}^n_+, \mathbf{x}^{k+1} \in \mathbb{R}^p_+
\end{aligned}$$

This step increments the subset of scenarios considered in the master problem. Note that, in the worst-case scenario for the algorithm, **MP** eventually becomes identical to the original problem (4-3) when all elements in $\mathcal{U}$ are considered. Nonetheless, the algorithm generally converges with only a small subset of critical scenarios selected by the subproblem **SP**.

7. Update $k = k + 1$ and return to step 2.

This algorithm supposes we are capable of solving **SP**. However, **SP** represents a nontrivial bilevel problem with integer variables in the lower level. In the following sections, the solution methodology utilized to solve **SP** is presented.

4.2 Reformulating the Subproblem

In general, the main strategy used to address bilevel max-min problems such as **SP** is to dualize the lower-level problem in order to derive a single-level equivalent that can be readily solved by commercial solvers running state-of-the-art branch-and-cut software. However, such a dualization is not possible when the lower level is a mixed-integer problem. Conversely, rather than deriving a single-level equivalent, this methodology aims to expand the bilevel **SP** into a trilevel problem that has a similar structure to the usual ARO framework in order to devise an inner CCGA loop.

Consider again the following formulation for **SP**:

$$
\begin{aligned}
\mathcal{Q}(\hat{\mathbf{y}}) = \max_{\mathbf{u}\in\mathcal{U}} \min_{\mathbf{z},\mathbf{x}} \quad & \mathbf{dx} + \mathbf{gz} \\
\text{subject to} \quad & \mathbf{Ex} + \mathbf{Gz} \geq \mathbf{f} - \mathbf{Ru} - \mathbf{D\hat{y}} \\
& \mathbf{Tz} \geq \mathbf{v} \\
& \mathbf{z} \in \mathbb{Z}_{+}^{n}, \mathbf{x} \in \mathbb{R}_{+}^{p}
\end{aligned}
\tag{4-8}
$$

By separating the integer variables from the continuous ones, we can obtain the following equivaleng trilevel formulation:

$$
\begin{aligned}
\mathcal{Q}(\hat{\mathbf{y}}) = \max_{\mathbf{u}\in\mathcal{U}} \min_{\mathbf{z}\in\mathcal{Z}} \ \mathbf{gz} \ + \ \min_{\mathbf{x}} \ & \mathbf{dx} \\
\text{subject to} \quad & \mathbf{Ex} \geq \mathbf{f} - \mathbf{Ru} - \mathbf{D\hat{y}} - \mathbf{Gz} \\
& \mathbf{x} \in \mathbb{R}_{+}^{p}
\end{aligned}
\tag{4-9}
$$

If we assume that the set of discrete recourse decisions is bounded, it is possible to exploit its countability. Note that such an assumption is not restrictive for practical problems in general. Thus, by considering $\mathcal{Z} = \{\mathbf{z}^r\}_{r=1}^{R}$, we can rewrite (4-9) as:

$$
\begin{aligned}
\mathcal{Q}(\hat{\mathbf{y}}) = \underset{\Theta,\mathbf{u}}{\text{maximize}} \quad & \Theta \\
\text{subject to} \quad & \Theta \leq \mathbf{gz}^r + \min_{\mathbf{x}^r} \Big\{ \mathbf{dx}^r : \mathbf{Ex}^r \geq \mathbf{f} - \mathbf{Ru} - \mathbf{D\hat{y}} - \mathbf{Gz}^r, \\
& \qquad \mathbf{x}^r \in \mathbb{R}_{+}^{p} \Big\}; \quad r = 1, \ldots, R \\
& \mathbf{u} \in \mathcal{U}.
\end{aligned}
\tag{4-10}
$$

In this formulation, we enumerate the possible values of $\mathbf{z}$, with $\mathbf{x}^r$ representing the decision variables corresponding to value $\mathbf{z}^r$. In the next step, for the general case, it would be necessary to derive the Karush-Kuhn-Tucker conditions [67] of the lower-level problem. However, in the context of energy redispatch, the lower-level problem assumes the form of a linear problem. Thus, strong duality holds, and an alternative simpler method may be used. This procedure is presented as follows.

First, it is necessary to dualize the lower-level minimization problem, which results in the following formulation:

$$\begin{aligned} \mathcal{Q}(\hat{\mathbf{y}}) = \underset{\Theta,\mathbf{u}}{\text{maximize}} \quad & \Theta \\ \text{subject to} \quad & \Theta \leq \mathbf{g}\mathbf{z}^r + \max_{\pi^r} \Big\{ (\mathbf{f} - \mathbf{R}\mathbf{u} - \mathbf{D}\hat{\mathbf{y}} - \mathbf{G}\mathbf{z}^r)^\top \pi^r : \\ & \qquad \mathbf{E}^\top \pi^r \leq \mathbf{d}^\top, \pi^r \in \mathbb{R}_+^{p'} \Big\}; \quad r = 1, \dots, R \\ & \mathbf{u} \in \mathcal{U}. \end{aligned} \tag{4-11}$$

Since Θ is constrained to be less or equal than $\mathbf{g}\mathbf{z}^r$ plus a maximum, then Θ is also less or equal than $\mathbf{g}\mathbf{z}^r$ plus all feasible solutions to that lower-level problem. Therefore, we can rewrite problem (4-11) by simply removing the maximization:

$$\begin{aligned} \mathcal{Q}(\hat{\mathbf{y}}) = \underset{\Theta,\pi^r,\mathbf{u}}{\text{maximize}} \quad & \Theta \\ \text{subject to} \quad & \Theta \leq \mathbf{g}\mathbf{z}^r + (\mathbf{f} - \mathbf{R}\mathbf{u} - \mathbf{D}\hat{\mathbf{y}} - \mathbf{G}\mathbf{z}^r)^\top \pi^r; \quad r = 1, \dots, R \\ & \mathbf{E}^\top \pi^r \leq \mathbf{d}^\top; \quad r = 1, \dots, R \\ & \pi^r \in \mathbb{R}_+^{p'}; \quad r = 1, \dots, R \\ & \mathbf{u} \in \mathcal{U}. \end{aligned} \tag{4-12}$$

Thus, (4-12) is an equivalent formulation of (4-4) that can be addressed through the standard CCGA just like the original problem. Note that, even though (4-12) has quadratic constraints due to the products between $\mathbf{u}$ and π^r, these constraints can be linearized through the use of big-M variables when $\mathbf{u}$ is a binary variable. This CCGA loop within the standard CCGA is denoted *inner CCGA*, while the overall algorithm comprising both the outer and inner loops is denoted *nested CCGA*.

4.3 The Inner Column-and-Constraint Algorithm

1. Initialize the lower and upper bounds as $LB = -\infty$, $UB = +\infty$, respectively, and the iteration counter as $m = 0$. Define a convergence tolerance ϵ^i.

2. Solve the *inner master problem* **IMP**.

$$
\begin{aligned}
\textbf{IMP}: \quad & \max_{\Theta, \pi^r, \mathbf{u}} \; \Theta \\
\text{subject to} \quad & \Theta \leq \mathbf{g}\mathbf{z}^r + (\mathbf{f} - \mathbf{R}\mathbf{u} - \mathbf{D}\hat{\mathbf{y}} - \mathbf{G}\mathbf{z}^r)^\top \pi^r; \quad r = 1, \ldots, m \\
& \mathbf{E}^\top \pi^r \leq \mathbf{d}^\top; \quad r = 1, \ldots, m \\
& \pi^r \in \mathbb{R}_+^{p'}; \quad r = 1, \ldots, m \\
& \mathbf{u} \in \mathcal{U}.
\end{aligned} \tag{4-13}
$$

IMP is a relaxation of **SP** because it is identical to (4-12) but with only a subset of m elements of $\mathcal{Z}$ being considered. Therefore, the solution of **IMP** yields an upper bound for **SP**. From the solution of **IMP**, we can also obtain the worst-case uncertainty realization $\mathbf{u}^*$.

3. Update upper bound using the solution of **IMP**:

$$UB = \mathcal{Q}(\hat{y}) = \Theta^* \tag{4-14}$$

If $UB - LB \leq \epsilon^i$, terminate.

4. Solve the *inner subproblem* **ISP**:

$$\underset{\mathbf{z} \in \mathcal{Z}, \mathbf{x} \in \mathcal{F}(\hat{\mathbf{y}}, \mathbf{u}^*)}{\text{minimize}} \quad \mathbf{d}\mathbf{x} + \mathbf{g}\mathbf{z} \tag{4-15}$$

5. Update lower bound using the solution of **ISP**:

$$LB = \max\{LB, \mathbf{d}\mathbf{x}^* + \mathbf{g}\mathbf{z}^*)\} \tag{4-16}$$

If $UB - LB \leq \epsilon^i$, terminate.

6. Add variables $(\mathbf{x}^{m+1}, \pi^{m+1})$ and the following constraints to **IMP**:

$$
\begin{aligned}
& \Theta \leq \mathbf{g}\mathbf{z}^{m+1} + (\mathbf{f} - \mathbf{R}\mathbf{u} - \mathbf{D}\hat{\mathbf{y}} - \mathbf{G}\mathbf{z}^{m+1})^\top \pi^{m+1} \\
& \mathbf{E}^\top \pi^{m+1} \leq \mathbf{d}^\top \\
& \mathbf{x}^{m+1} \in \mathbb{R}_+^{p}, \; \pi^{m+1} \in \mathbb{R}_+^{p'}.
\end{aligned}
$$

7. Update $m = m + 1$ and return to step 2.

For more details on the nested CCGA, we refer the interested reader to [32].

5 Contingency-Constrained Unit Commitment with Co-Optimized Pre- and Post-Contingency Transmission Switching

In this chapter, we present a CCUC model that co-optimizes energy and reserve offers with pre- and post-contingency TS actions. The model is formulated over a multi-period setting and considers inter-temporal constraints such as ramping limits. Furthermore, we provide a novel and enhanced version of the nested CCGA as a solution methodology to tackle the challenging mixed-integer program resulting from the problem formulation. Finally, numerical results that illustrate relevant benefits and effects in system operation are presented.

5.1 Problem Formulation

The proposed model is cast as a mixed-integer program driven by the minimization of the sum of the offer costs and the worst-case power imbalance cost:

$$\underset{\substack{\theta^c_{bt},\Phi^w,\Phi^{-c}_{bt},\Phi^{+c}_{bt}\\ c^{sd}_{it},c^{su}_{it},f^c_{lt},p^c_{it}\\ r^{dn}_{it},r^{up}_{it},v_{it},z^c_{lt}}}{\text{minimize}} \quad \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}\Big[C^P_{it}(p^0_{it},v_{it}) + C^{up}_{it}r^{up}_{it} + C^{dn}_{it}r^{dn}_{it} + c^{su}_{it} + c^{sd}_{it}\Big] + C^I\Phi^w \tag{5-1}$$

subject to:

$$\Phi^w \geq \sum_{t\in\mathcal{T}}\sum_{b\in\mathcal{B}}(\Phi^{-c}_{bt} + \Phi^{+c}_{bt});\ \forall c\in\mathcal{C} \tag{5-2}$$

$$\sum_{i\in\mathcal{I}_b} p^c_{it} + \sum_{l\in\mathcal{L}|to(l)=b} f^c_{lt} - \sum_{l\in\mathcal{L}|fr(l)=b} f^c_{lt} = d_{bt} + \Phi^{-c}_{bt} - \Phi^{+c}_{bt};\quad \forall b\in\mathcal{B},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{5-3}$$

$$-M_l(1-A^c_{lt}z^c_{lt}) \leq f^c_{lt} - \frac{1}{x_l}(\theta^c_{fr(l)t} - \theta^c_{to(l)t}) \leq M_l(1-A^c_{lt}z^c_{lt});\quad \forall l\in\mathcal{L},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{5-4}$$

$$-A^c_{lt}z^c_{lt}\overline{F}_l \leq f^c_{lt} \leq A^c_{lt}z^c_{lt}\overline{F}_l;\ \forall l\in\mathcal{L},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{5-5}$$

$$z^c_{lt} = 1;\ \forall l\in\mathcal{L}\backslash\mathcal{L}^{TS},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{5-6}$$

$$v_{it} A^0_{it} \underline{P}_{it} \leq p^0_{it} \leq v_{it} A^0_{it} \overline{P}_{it};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}7)$$

$$A^c_{it}(p^0_{it} - r^{dn}_{it}) \leq p^c_{it} \leq A^c_{it}(p^0_{it} + r^{up}_{it});\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T}, \forall c \in \mathcal{C} \quad (5\text{-}8)$$

$$0 \leq r^{up}_{it} \leq \overline{R}^{up}_{it};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}9)$$

$$0 \leq r^{dn}_{it} \leq \overline{R}^{dn}_{it};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}10)$$

$$p^0_{it} - p^0_{it-1} \leq RU_i v_{it-1} + SU_i(v_{it} - v_{it-1}) + \overline{P}_{it}(1 - v_{it}); \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}11)$$

$$p^0_{it-1} - p^0_{it} \leq RD_i v_{it} + SD_i(v_{it-1} - v_{it}) + \overline{P}_{it}(1 - v_{it-1}); \quad \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}12)$$

$$\{c^{sd}_{it}\}_{t\in\mathcal{T}}, \{c^{su}_{it}\}_{t\in\mathcal{T}}, \{v_{it}\}_{t\in\mathcal{T}} \in \mathcal{F}_i;\ \forall i \in \mathcal{I} \quad (5\text{-}13)$$

$$\Phi^{-c}_{bt} \geq 0, \Phi^{+c}_{bt} \geq 0;\ \forall b \in \mathcal{B}, \forall t \in \mathcal{T}, \forall c \in \mathcal{C} \quad (5\text{-}14)$$

$$z^c_{lt} \in \{0,1\};\ \forall l \in \mathcal{L}^{TS}, \forall t \in \mathcal{T}, \forall c \in \mathcal{C} \quad (5\text{-}15)$$

$$v_{it} \in \{0,1\};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T}. \quad (5\text{-}16)$$

The objective function minimized in (5-1) comprises the offered costs of pre-contingency power generation, up- and down-spinning reserve allocation, start-ups, and shutdowns, as well as the cost of the worst-case power imbalance. Constraints (5-2) ensure that Φ^w represents the worst-case power imbalance by making it greater than or equal to the imbalance under every contingency state. Based on [68], a dc power flow is modeled by expressions (5-3), characterizing power balances, and (5-4), representing line flows while taking into account PC-TS and line availability. Line flow capacity limits are modeled in (5-5). As per (5-6), non-switchable lines are always switched on. In (5-7), power outputs are bounded. In (5-8), the relationship between power outputs and reserve contributions is characterized. Note that generator availability is considered in (5-7) and (5-8). In (5-9) and (5-10), bounds on up- and down-spinning reserve contributions are respectively imposed. Expressions (5-11) and (5-12) model the ramping limitations, which are solely enforced in the pre-contingency state, as done in [13, 16, 33, 34, 53]. Start-up and shutdown offer costs as well as minimum up and down times are formulated in (5-13) in a compact way; more details can be found in [69]. Constraints (5-14) ensure the non-negativity of the variables used in the linearization of the absolute value of the power imbalance, Φ^{-c}_{bt} and Φ^{+c}_{bt}, representing the negative and positive parts of the imbalance, respectively. Finally, TS and generation scheduling are modeled by binary variables in (5-15) and (5-16), respectively. In this formulation, the contingency state $c = 0$ represents the pre-contingency state, wherein all generators and transmission lines are available.

In (5-1)–(5-16), contingency states associated with the prescribed security criterion are characterized through parameters A_{it}^c and A_{lt}^c. Thus, a compact formulation for the security criterion is as follows:

$$\boldsymbol{f}\Big(\{A_{it}^c\}_{i\in\mathcal{I}}, \{A_{lt}^c\}_{l\in\mathcal{L}}\Big) \geq \mathbf{0};\ \forall t \in \mathcal{T}, \forall c \in \mathcal{C} \quad (5\text{-}17)$$

where $\boldsymbol{f}(\cdot)$ is a set of linear constrained functions.

As an example, for an $n-K$ criterion, expressions (5-17) become:

$$\sum_{i\in\mathcal{I}} A_{it}^c + \sum_{l\in\mathcal{L}} A_{lt}^c \geq |\mathcal{I}| + |\mathcal{L}| - K;\ \forall t \in \mathcal{T}, \forall c \in \mathcal{C}. \quad (5\text{-}18)$$

Similarly, an $n-K^G-K^L$ criterion, where K^G and K^L denote the number of out-of-service generators and transmission lines, respectively, gives rise to:

$$\sum_{i\in\mathcal{I}} A_{it}^c \geq |\mathcal{I}| - K^G;\ \forall t \in \mathcal{T}, \forall c \in \mathcal{C} \quad (5\text{-}19)$$

$$\sum_{l\in\mathcal{L}} A_{lt}^c \geq |\mathcal{L}| - K^L;\ \forall t \in \mathcal{T}, \forall c \in \mathcal{C}. \quad (5\text{-}20)$$

5.2 Equivalent Adjustable Robust Formulation

The monolithic formulation (5-1)–(5-16) can be recast within an ARO framework, presented in Chapter 3, in the following manner:

$$\underset{\substack{\theta_{bt},\Phi^w,c_{it}^{sd},c_{it}^{su},f_{lt},\\ p_{it},r_{it}^{dn},r_{it}^{up},v_{it},z_{lt}}}{\text{minimize}} \quad \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}} \Big[C_{it}^P(p_{it}, v_{it}) + C_{it}^{up} r_{it}^{up} + C_{it}^{dn} r_{it}^{dn} + c_{it}^{su} + c_{it}^{sd}\Big] + C^I \Phi^w \quad (5\text{-}21)$$

subject to:

$$\sum_{i\in\mathcal{I}_b} p_{it} + \sum_{l\in\mathcal{L}|to(l)=b} f_{lt} - \sum_{l\in\mathcal{L}|fr(l)=b} f_{lt} = d_{bt};\ \forall b \in \mathcal{B}, \forall t \in \mathcal{T} \quad (5\text{-}22)$$

$$-M_l(1-z_{lt}) \leq f_{lt} - \frac{1}{x_l}(\theta_{fr(l)t} - \theta_{to(l)t}) \leq M_l(1-z_{lt});\ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (5\text{-}23)$$

$$-z_{lt}\overline{F}_l \leq f_{lt} \leq z_{lt}\overline{F}_l;\ \forall l \in \mathcal{L},\ \forall t \in \mathcal{T} \quad (5\text{-}24)$$

$$z_{lt} = 1;\ \forall l \in \mathcal{L}\backslash\mathcal{L}^{TS}, \forall t \in \mathcal{T} \quad (5\text{-}25)$$

$$p_{it} - r_{it}^{dn} \geq \underline{P}_{it} v_{it};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}26)$$

$$p_{it} + r_{it}^{up} \leq \overline{P}_{it} v_{it};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}27)$$

$$0 \leq r_{it}^{up} \leq \overline{R}_{it}^{up};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}28)$$

$$0 \leq r_{it}^{dn} \leq \overline{R}_{it}^{dn};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}29)$$

$$p_{it} - p_{it-1} \leq RU_i v_{it-1} + SU_i(v_{it} - v_{it-1}) + \overline{P}_{it}(1 - v_{it}); \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}30)$$

$$p_{it-1} - p_{it} \leq RD_i v_{it} + SD_i(v_{it-1} - v_{it}) + \overline{P}_{it}(1 - v_{it-1});$$
$$\forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}31)$$

$$\{c_{it}^{sd}\}_{t\in\mathcal{T}}, \{c_{it}^{su}\}_{t\in\mathcal{T}}, \{v_{it}\}_{t\in\mathcal{T}} \in \mathcal{F}_i;\ \forall i \in \mathcal{I} \quad (5\text{-}32)$$

$$v_{it} \in \{0,1\};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}33)$$

$$z_{lt} \in \{0,1\};\ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (5\text{-}34)$$

$$\Phi^w = \underset{\Phi, a_{it}, a_{lt}}{\text{maximize}} \Bigg\{ \Phi \quad (5\text{-}35)$$

subject to:

$$a_{it} \in \{0,1\};\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}36)$$

$$a_{lt} \in \{0,1\};\ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (5\text{-}37)$$

$$\boldsymbol{f}(\{a_{it}\}_{i\in\mathcal{I}}, \{a_{lt}\}_{l\in\mathcal{L}}) \geq 0;\ \forall t \in \mathcal{T} \quad (5\text{-}38)$$

$$\Phi = \underset{\substack{\tilde{\theta}_{bt}, \tilde{\Phi}_{bt}^-, \tilde{\Phi}_{bt}^+, \\ \tilde{f}_{lt}, \tilde{p}_{it}, \tilde{z}_{lt}}}{\text{minimize}} \Bigg[\sum_{b\in\mathcal{B}} \sum_{t\in\mathcal{T}} \left(\tilde{\Phi}_{bt}^- + \tilde{\Phi}_{bt}^+ \right) \quad (5\text{-}39)$$

subject to: (5-40)

$$\sum_{i\in\mathcal{I}_b} \tilde{p}_{it} + \sum_{l\in\mathcal{L}|to(l)=b} \tilde{f}_{lt} - \sum_{l\in\mathcal{L}|fr(l)=b} \tilde{f}_{lt} = d_{bt} + \tilde{\Phi}_{bt}^- - \tilde{\Phi}_{bt}^+;\ \forall b \in \mathcal{B}, \forall t \in \mathcal{T} \quad (5\text{-}41)$$

$$-M_l(1 - a_{lt}\tilde{z}_{lt}) \leq \tilde{f}_{lt} - \frac{1}{x_l}(\tilde{\theta}_{fr(l)t} - \tilde{\theta}_{to(l)t}) \leq M_l(1 - a_{lt}\tilde{z}_{lt});$$
$$\forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (5\text{-}42)$$

$$-a_{lt}\tilde{z}_{lt}\overline{F}_l \leq \tilde{f}_{lt} \leq a_{lt}\tilde{z}_{lt}\overline{F}_l;\ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (5\text{-}43)$$

$$a_{it}(p_{it} - r_{it}^{dn}) \leq \tilde{p}_{it} \leq a_{it}(p_{it} + r_{it}^{up});\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (5\text{-}44)$$

$$\tilde{z}_{lt} = 1;\ \forall l \in \mathcal{L} \backslash \mathcal{L}^{TS} \quad (5\text{-}45)$$

$$\tilde{\Phi}_{bt}^- \geq 0, \tilde{\Phi}_{bt}^+ \geq 0;\ \forall b \in \mathcal{B}, \forall t \in \mathcal{T} \quad (5\text{-}46)$$

$$\tilde{z}_{lt} \in \{0,1\};\ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (5\text{-}47)$$

$$\tilde{p}_{it} \geq 0;\ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \Bigg] \Bigg\}. \quad (5\text{-}48)$$

In this formulation, availability parameters A_{it}^c and A_{lt}^c are replaced with binary variables a_{it} and a_{lt} and a trilevel structure is used to model the two-stage problem. As a result, system operation under contingency is implicitly modeled and indices c are dropped. Variables representing operation under contingency are denoted with a tilde. As discussed in Chapter 3, this trilevel problem is suitable for the application of the nested CCGA.

5.3 Solution Methodology

Directly solving problem (5-1)–(5-16) may be computationally intractable due to the need to explicitly model system operation under all contingency states associated with the pre-specified security criterion. In the recent CCUC literature, the concept of umbrella contingencies [70, 71] has been widely utilized to enable the use of master-subproblem decomposition techniques [51, 52] for problems structurally similar to (5-1)–(5-16). Such decomposition methods have become the standard solution procedures for CCUC [8, 9, 12, 13, 16]. In this context, the subproblem or oracle problem is a bilevel program responsible for finding the worst-case contingency state for a given schedule provided by the preceding master problem. Such a contingency state is then inserted into the master problem, which outputs a new schedule.

Unfortunately, the presence of binary variables associated with post-contingency TS in the lower level of the oracle problem makes problem (5-1)–(5-16) unsuitable for the standard single-loop master-oracle structures used for CCUC [51, 52]. As a salient methodological feature, we propose a novel and enhanced application of the nested CCGA [32] presented in Chapter 4.

5.3.1 Outer Loop

The outer loop represents the master-oracle structure that is iterated until convergence to determine the solution of the original problem (5-1)–(5-16). The outer loop converges once the bounds provided by the master problem and the oracle problem are within a pre-specified tolerance ϵ^o.

5.3.1.1 Master Problem

The master problem is a relaxation of the original problem (5-1)–(5-16) where, at each outer-loop iteration k, $\mathcal{C}$ is replaced with a subset of contingency states $\mathcal{C}_k$. Solving the master problem yields decisions $p_{it}^{0(k)}$, $v_{it}^{(k)}$, $r_{it}^{up(k)}$, and $r_{it}^{dn(k)}$, which represent the optimal schedule for the set of states $\mathcal{C}_k$. Since the master problem constitutes a relaxation of the original problem, its solution allows computing a lower bound for the optimal value of the objective function (5-1):

$$LB^{(k)} = \sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} \Bigg[C_{it}^{P}(p_{it}^{0(k)}, v_{it}^{(k)}) + C_{it}^{up} r_{it}^{up(k)} + C_{it}^{dn} r_{it}^{dn(k)} + c_{it}^{su(k)} + c_{it}^{sd(k)} \Bigg] + C^{I} \Phi^{w(k)}. \quad (5\text{-}49)$$

5.3.1.2 Oracle Problem

The goal of the oracle problem is to identify the worst-case contingency state for a given schedule obtained by the preceding master problem. To that end, the worst-case setting is implemented by a bilevel programming framework [9, 12–14, 16]. In the bilevel oracle problem, the upper level is responsible for finding the contingency state maximizing the power imbalance, while the lower level obtains the optimal system reaction. The oracle problem for (5-1)–(5-16) is presented below. For the sake of clarity, a tilde is used to denote the decision variables modeling system operation under contingency, whereas dual variables are shown in parentheses.

$$\Phi^{(k)} = \max_{a_{it}, a_{lt}} \min_{\substack{\tilde{\theta}_{bt}, \tilde{\Phi}^-_{bt}, \tilde{\Phi}^+_{bt}, \\ \tilde{f}_{lt}, \tilde{p}_{it}, \tilde{z}_{lt}}} \sum_{b \in \mathcal{B}} \sum_{t \in \mathcal{T}} \left(\tilde{\Phi}^-_{bt} + \tilde{\Phi}^+_{bt} \right) \tag{5-50}$$

subject to:

$$a_{it} \in \{0,1\}; \ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{5-51}$$

$$a_{lt} \in \{0,1\}; \ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \tag{5-52}$$

$$\boldsymbol{f}(\{a_{it}\}_{i \in \mathcal{I}}, \{a_{lt}\}_{l \in \mathcal{L}}) \geq \mathbf{0}; \ \forall t \in \mathcal{T} \tag{5-53}$$

$$\sum_{i \in \mathcal{I}_b} \tilde{p}_{it} + \sum_{l \in \mathcal{L} | to(l) = b} \tilde{f}_{lt} - \sum_{l \in \mathcal{L} | fr(l) = b} \tilde{f}_{lt} = d_{bt} + \tilde{\Phi}^-_{bt} - \tilde{\Phi}^+_{bt} : (\beta_{bt}); \ \forall b \in \mathcal{B}, \forall t \in \mathcal{T} \tag{5-54}$$

$$- M_l(1 - a_{lt}\tilde{z}_{lt}) \leq \tilde{f}_{lt} - \frac{1}{x_l}\left(\tilde{\theta}_{fr(l)t} - \tilde{\theta}_{to(l)t}\right) : (\omega_{lt}); \ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \tag{5-55}$$

$$\tilde{f}_{lt} - \frac{1}{x_l}\left(\tilde{\theta}_{fr(l)t} - \tilde{\theta}_{to(l)t}\right) \leq M_l(1 - a_{lt}\tilde{z}_{lt}) : (\zeta_{lt}); \ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \tag{5-56}$$

$$- a_{lt}\tilde{z}_{lt}\overline{F}_l \leq \tilde{f}_{lt} \leq a_{lt}\tilde{z}_{lt}\overline{F}_l : (\pi_{lt}, \sigma_{lt}); \ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \tag{5-57}$$

$$\tilde{z}_{lt} = 1; \ \forall l \in \mathcal{L} \backslash \mathcal{L}^{TS}, \forall t \in \mathcal{T} \tag{5-58}$$

$$a_{it}(p^{0(k)}_{it} - r^{dn(k)}_{it}) \leq \tilde{p}_{it} \leq a_{it}(p^{0(k)}_{it} + r^{up(k)}_{it}) : (\gamma_{it}, \chi_{it}); \ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{5-59}$$

$$\tilde{\Phi}^-_{bt} \geq 0, \tilde{\Phi}^+_{bt} \geq 0; \ \forall b \in \mathcal{B}, \forall t \in \mathcal{T} \tag{5-60}$$

$$\tilde{z}_{lt} \in \{0,1\}; \ \forall l \in \mathcal{L}^{TS}, \forall t \in \mathcal{T}. \tag{5-61}$$

In (5-50), the max-min structure allows identifying the contingency state resulting in the maximum power imbalance while taking into consideration the best reaction. Expressions (5-51) and (5-52) characterize the variables representing the availability of generators and transmission lines, respectively. In (5-53), the prescribed security criterion is enforced using the vector $\boldsymbol{f}(\cdot)$ explained in Section 5.1. Based on [68], constraints (5-54)–(5-56) correspond to the dc power flow model. Bounds for post-contingency line flows are set in (5-57). In (5-58), non-switchable lines are forced to be switched on. Constraints (5-59) impose bounds on post-contingency power outputs based on allocated reserves. Finally, (5-60) and (5-61) define the variables modeling power imbalance and post-contingency TS, respectively.

Note that, at each outer-loop iteration k, the following upper bound for the optimal cost can be derived:

$$UB^{(k)} = \sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} \Bigg[C^P_{it}(p^{0(k)}_{it}, v^{(k)}_{it}) + C^{up}_{it} r^{up(k)}_{it} + C^{dn}_{it} r^{dn(k)}_{it} + c^{su(k)}_{it} + c^{sd(k)}_{it} \Bigg] + C^I \Phi^{(k)}. \tag{5-62}$$

5.3.2 Inner Loop

At each outer-loop iteration k, an inner master problem and an inner subproblem are iterated until convergence to determine the solution of the bilevel oracle problem (5-50)–(5-61). The inner loop converges once the bounds provided by the inner master problem and the inner subproblem are within a prescribed tolerance ϵ^i.

5.3.2.1 Inner Subproblem

The inner subproblem comprises the lower-level optimization of the oracle problem for a given contingency state, i.e., the minimization in (5-50) subject to constraints (5-54)–(5-61) where a_{it} and a_{lt} are replaced with the optimal values provided by the previous inner master problem. At each inner-loop iteration m, the solution to the inner subproblem provides a lower bound for the optimal value of the objective function optimized in the oracle problem. The optimal line switching decisions resulting from the inner subproblem at inner-loop iteration m, $\tilde{z}^{(m)}_{lt}$, are fed to the following inner master problem.

5.3.2.2 Inner Master Problem

The inner master problem represents a single-level relaxation of (5-50)–(5-61). Following the methodology presented in [32], the inner master problem at outer-loop iteration k and inner-loop iteration j is formulated as follows:

$$\underset{\substack{\beta_{bt}^m,\gamma_{it}^m,\zeta_{lt}^m,\pi_{lt}^m,\sigma_{lt}^m,\\ \Phi^{ap},\chi_{it}^m,\omega_{lt}^m,a_{it},a_{lt}}}{\text{maximize}} \quad \Phi^{ap} \tag{5-63}$$

subject to:

$$\Phi^{ap} \leq \sum_{t\in\mathcal{T}} \Bigg\{ \sum_{b\in\mathcal{B}} \beta_{bt}^m d_{bt} + \sum_{l\in\mathcal{L}} \Bigg[\omega_{lt}^m M_l \Big(a_{lt}\tilde{z}_{lt}^{(m)} - 1 \Big) + \zeta_{lt}^m M_l \Big(a_{lt}\tilde{z}_{lt}^{(m)} - 1 \Big) - \pi_{lt}^m a_{lt}\tilde{z}_{lt}^{(m)}\overline{F}_l - \sigma_{lt}^m a_{lt}\tilde{z}_{lt}^{(m)}\overline{F}_l \Bigg] + \sum_{i\in\mathcal{I}} \Bigg[\gamma_{it}^m a_{it}\Big(p_{it}^{0(k)} - r_{it}^{dn(k)} \Big) - \chi_{it}^m a_{it}\Big(p_{it}^{0(k)} + r_{it}^{up(k)} \Big) \Bigg] \Bigg\}; \; m = 1,\ldots,j \tag{5-64}$$

$$\text{Constraints (5-51)–(5-53)} \tag{5-65}$$

$$\omega_{lt}^m \geq 0, \zeta_{lt}^m \geq 0, \pi_{lt}^m \geq 0, \sigma_{lt}^m \geq 0; \; \forall l \in \mathcal{L}, \forall t \in \mathcal{T}, m = 1,\ldots,j \tag{5-66}$$

$$\gamma_{it}^m \geq 0, \chi_{it}^m \geq 0; \; \forall i \in \mathcal{I}, \forall t \in \mathcal{T}, m = 1,\ldots,j \tag{5-67}$$

$$\beta_{b(i)t}^m + \gamma_{it}^m - \chi_{it}^m \leq 0; \; \forall i \in \mathcal{I}, \forall t \in \mathcal{T}, m = 1,\ldots,j \tag{5-68}$$

$$\beta_{to(l)t}^m - \beta_{fr(l)t}^m + \omega_{lt}^m - \zeta_{lt}^m + \pi_{lt}^m - \sigma_{lt}^m = 0; \quad \forall l \in \mathcal{L}, \forall t \in \mathcal{T}, m = 1,\ldots,j \tag{5-69}$$

$$-1 \leq \beta_{bt}^m \leq 1; \; \forall b \in \mathcal{B}, \forall t \in \mathcal{T}, m = 1,\ldots,j \tag{5-70}$$

$$\sum_{l\in\mathcal{L}|fr(l)=b} \frac{\omega_{lt}^m - \zeta_{lt}^m}{x_l} + \sum_{l\in\mathcal{L}|to(l)=b} \frac{\zeta_{lt}^m - \omega_{lt}^m}{x_l} = 0; \quad \forall b \in \mathcal{B}, \forall t \in \mathcal{T}, m = 1,\ldots,j. \tag{5-71}$$

Expression (5-64) contains nonlinearities in the form of products of decision variables. Using the algebraic results presented in [72], these bilinear terms can be linearized and, thus, the inner master problem can be cast as a single-level mixed-integer linear program. The optimal values of variables a_{it} and a_{lt} obtained from the resolution of problem (5-63)–(5-71) are used as parameters in the subsequent inner subproblem. Since the inner master problem is a relaxation of (5-50)–(5-61), its solution allows computing an upper bound for the optimal value of the objective function optimized in the oracle problem.

5.3.3 Algorithm Overview

Fig. 5.1 presents a flowchart of the proposed solution methodology. The fact that $|\mathcal{C}_k| \ll |\mathcal{C}|$ addresses the problem of having to explicitly consider a prohibitive number of contingency states. The key idea is to add to $\mathcal{C}_k$ the worst-case state identified by the oracle problem at each outer-loop iteration k.

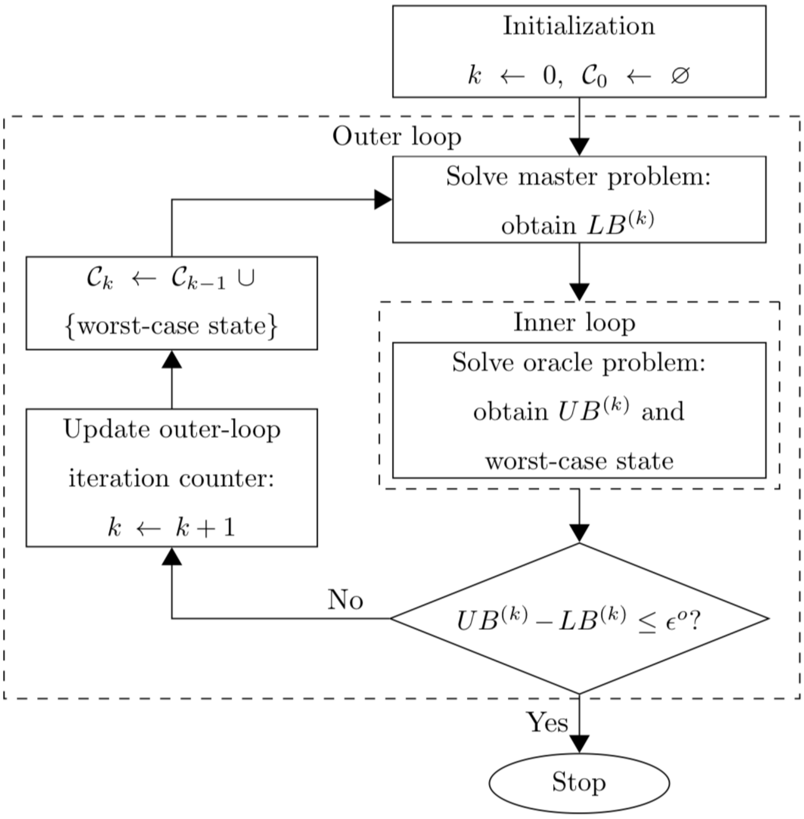

Figure 5.1: Flowchart of the proposed algorithm.

The master problem converges to the full problem, as $\mathcal{C}_k$ eventually becomes equal to $\mathcal{C}$ should all possible contingency states be examined. It is worth emphasizing that the main advantage of this methodology is that attaining the optimal solution to the original problem (5-1)–(5-16) generally requires considering a small subset of contingency states. The nested iterative process is stopped when the difference between the upper and lower cost bounds is less than or equal to a pre-specified outer-loop tolerance ϵ^o.

5.3.4 Performance Enhancement

In the nested CCGA, the number of variables and constraints in the outer-loop master problem iteratively grows. Therefore, the computational effort required to attain convergence is strongly related to the total number of outer-loop iterations. In addition, the relaxation of the original problem provided by the master problem at the first outer-loop iterations tends to be loose due to the empty or small contingency set considered. In other words, the primal cuts provided by these very first iterations are seldom tight and do not usually represent umbrella contingencies.

As a relevant performance enhancement technique, valid constraints associated with generator outages in a simplified single-bus model can be incorporated in the master problem. This addition substantially increases the quality of the relaxation along the first iterations. As a result, the total number of outer loops is reduced, which yields significant speed-ups.

The simplified problem considering a single-bus model and generator outages can be formulated as [8]:

$$\underset{\substack{\Phi^w, p^0_{it}, c^{sd}_{it},\\ c^{su}_{it}, r^{up}_{it}, v_{it}}}{\text{minimize}} \sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} \left[C^P_{it}(p^0_{it}, v_{it}) + C^{up}_{it} r^{up}_{it} + c^{su}_{it} + c^{sd}_{it} \right] + C^I \Phi^w \tag{5-72}$$

subject to:

$$\sum_{i \in \mathcal{I}} p^0_{it} = \sum_{b \in \mathcal{B}} d_{bt}; \; \forall t \in \mathcal{T} \tag{5-73}$$

$$p^0_{it} + r^{up}_{it} \leq \overline{P}_{it} v_{it}; \; \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{5-74}$$

$$p^0_{it} \geq \underline{P}_{it} v_{it}; \; \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{5-75}$$

$$\text{Constraints (5-9), (5-11)–(5-13), and (5-16)} \tag{5-76}$$

$$\Phi^w \geq \sum_{b \in \mathcal{B}} \sum_{t \in \mathcal{T}} d_{bt} - p^w \tag{5-77}$$

$$p^w = \underset{a_{it}}{\text{minimize}} \sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} a_{it}(p^0_{it} + r^{up}_{it}) \tag{5-78}$$

subject to:

$$\sum_{i \in \mathcal{I}} a_{it} \geq |\mathcal{I}| - K : (\lambda_t); \; \forall t \in \mathcal{T} \tag{5-79}$$

$$0 \leq a_{it} \leq 1 : (\xi_{it}); \; \forall i \in \mathcal{I}, \forall t \in \mathcal{T}. \tag{5-80}$$

Using the duality theory of linear programming, expressions (5-77)–(5-80) can be equivalently cast as:

$$\Phi^w \geq \sum_{t \in \mathcal{T}} \left[\sum_{b \in \mathcal{B}} d_{bt} - (|\mathcal{I}| - K)\lambda_t + \sum_{i \in \mathcal{I}} \xi_{it} \right] \tag{5-81}$$

$$\lambda_t - \xi_{it} \leq p^0_{it} + r^{up}_{it}; \; \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{5-82}$$

$$\xi_{it} \geq 0; \; \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \tag{5-83}$$

$$\lambda_t \geq 0; \; \forall t \in \mathcal{T}. \tag{5-84}$$

For every generator outage, expressions (5-81)–(5-84) (or (5-77)–(5-80), likewise) guarantee that the sum of up-spinning reserve contributions of all available generators is at least equal to the generation of the out-of-service generators. As this condition also holds for the original CCUC model, expressions (5-81)–(5-84) form a set of valid constraints that can be added to the outer-loop master problem without cutting off the optimal solution.

5.4 Numerical Results

In order to demonstrate the effective performance of co-optimized pre- and post-contingency TS, two case studies were analyzed. The first benchmark is an illustrative example relying on the 4-bus system described in [38] with the addition of inter-temporal constraints. The second case study is a modified version of the IEEE 118-bus system. The modifications include the increase in nodal consumption and the reduction of certain line capacities in order to stress the system. In both cases, the standard $n-1$ security criterion and a 24-hour time span were considered. In this case, contingencies are considered as a single entity throughout the entire time span. For example, if we consider a certain line is under contingency, then that line is unavailable from the first time period until the last one. For the 4-bus system, contingencies were considered for all generators and lines. For the 118-bus system, contingencies were considered for the 17 generators with rated power capacity above 200 MW and for the 12 tie lines connecting the three areas in which the system can be split [31]. For both systems, it was assumed that producers offer linear cost functions and that the cost of power imbalance C^I is 10 times the variable cost coefficient of the most expensive generator. For the sake of reproducibility, system data are provided in [73].

In both case studies, three formulations were compared, namely 1) a model disregarding TS, denoted by No TS; 2) a model solely considering co-optimized pre-contingency TS, as done in [33], which is referred to as PreTS; and 3) a model with co-optimized pre- and post-contingency TS, denoted by PPTS. The enhanced nested CCGA with the valid constraints described in Section 5.3.4 was employed to address PPTS, while No TS and PreTS were solved through a standard single-loop CCGA, i.e., the nested CCGA excluding the inner loop. The execution of the decomposition procedures was stopped when either a solution was found within a 1% optimality tolerance or a timeout limit of 24 hours was reached. All tests were conducted utilizing the Julia language and CPLEX 12.8 on an Intel Core i7-490K processor at 4.00 GHz and 32 GB of RAM.

5.4.1 Choice of Switchable Lines

The choice of lines to consider as switchable is a non-trivial problem. Considering all lines as switchable may lead to prohibitive amounts of binary variables for larger instances, thereby rendering the problem intractable. However, it can be shown that a small number of switchable lines is sufficient

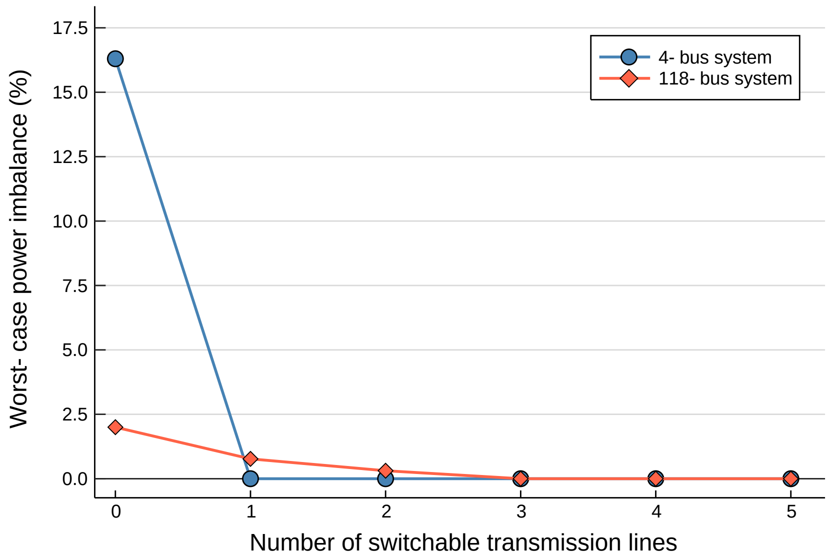

Figure 5.2: Worst-case power imbalance per number of switchable lines.

to obtain significant improvements over the case with no TS, even resulting in the same power imbalance reduction as when all lines are switchable. This finding may be beneficial for practical implementation purposes due to the considerable decrease in the number of binary variables of the resulting optimization problem.

Thus, a practical and effective solution is to utilize simple heuristics to obtain reduced sets of critical switchable lines. There are several straightforward ways of finding the best single switchable line – one possibility is to solve problem (5-1)–(5-16) with $\mathcal{L}^{TS}$ as every single line and pick the best one. Next, the single best switchable line is added to $\mathcal{L}^{TS}$ and we solve the problem again to find the best switchable line coupled with the previous one. This very simple heuristic results in a reduced set of switchable lines that offer significant benefits to the system.

Fig. 5.2 presents the worst-case power imbalance in terms of system load resulting from the CCUC with PPTS for the 4-bus and 118-bus systems under an $n-1$ criterion and over a single-period time span. It can be seen that the 4-bus system is able to avoid power imbalance scenarios with just one switchable line, namely line 3-4. Meanwhile, the 118-bus system is able to nullify power imbalance levels with three switchable lines, namely lines 3-5, 7-12, and 8-30. Taking into account that the 118-bus system has 186 lines, a subset of three switchable lines is comparably very small. This also corroborates the findings in [38] for the IEEE 30-bus system. Throughout the numerical results, we will utilize these reduced sets of switchable lines as the switchable sets $\mathcal{L}^{TS}$ for each system.

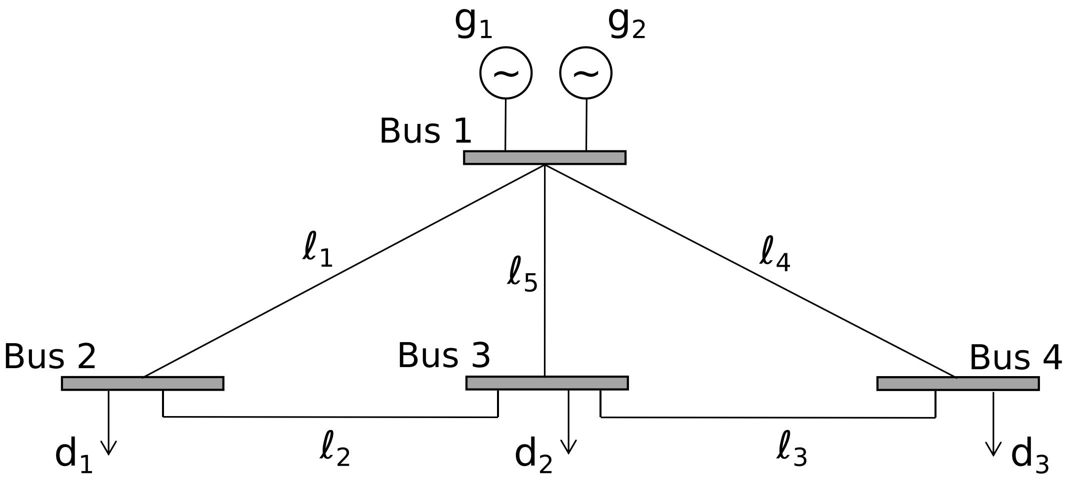

Figure 5.3: The illustrative 4-bus system.

Hours	0	1	2	3	4	5	6	7	8	9	10	11
No TS	1	1	1	1	1	1	1	1	1	1	1	1
PreTS	1	1	1	1	1	1	1	1	0	0	0	0
PPTS	0	0	0	0	0	0	0	0	0	0	0	0
Hours	12	13	14	15	16	17	18	19	20	21	22	23
No TS	1	1	1	1	1	1	1	1	1	1	1	1
PreTS	1	1	1	1	1	0	0	0	1	1	1	1
PPTS	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.1: Pre-Contingency Statuses of Line 3 for the 4-Bus System

5.4.2 4-Bus Example

The 4-bus system displayed in Fig. 5.3 is useful to illustrate the benefits of PPTS, which are a consequence of significantly changing the system operation. This result is shown in Table 5.1, which lists the pre-contingency statuses of line 3 along the scheduling horizon, i.e., z_{3t}^{0}, provided by the three models. Unlike No TS and PreTS, the co-optimization of post-contingency TS leads to switching off this line throughout the time span. Thus, by co-optimizing post-contingency TS, it is possible to obtain a better pre-contingency line status schedule. Finally, the impact of post-contingency TS on solution quality is evidenced by the results displayed in Table 5.2, where it is shown that PPTS decreases the worst-case imbalance from 16.3% and 8.4% down to 0% while also reducing system costs by 54.6% and 38.8% when compared to No TS and PreTS, respectively.

5.4.3

System		No TS	PreTS	PPTS
4-bus	System Cost ($)	753,885	558,698	341,827
	Φ^w (%)	16.3	8.4	0.0
118-bus	System Cost ($)	3,019,163	2,671,966	1,926,824
	Φ^w (%)	1.1	0.8	0.0

Table 5.2: Impact of Post-Contingency TS on Solution Quality

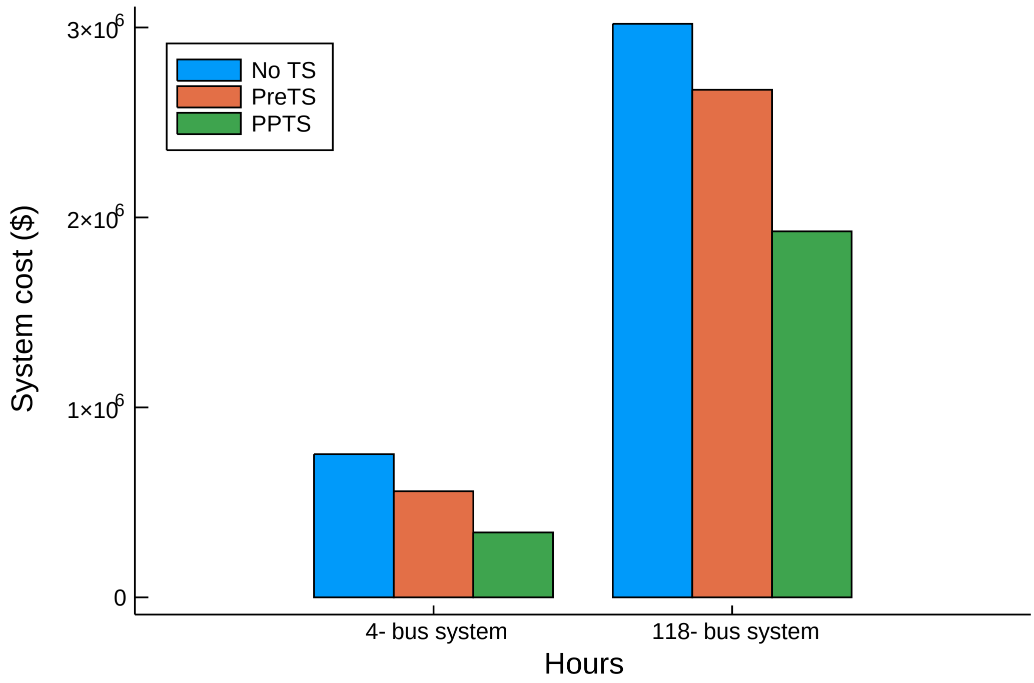

Figure 5.4: Comparison of the system costs for the 4-bus and 118-bus systems for each formulation.

IEEE 118-Bus System

As shown in Table 5.2, PPTS successfully ensured power balance for all possible contingency states within the pre-specified security criterion, while No TS and PreTS resulted in worst-case power imbalances of 1.1% and 0.8%. These results further corroborate the fact that PPTS allows obtaining schedules that better withstand contingencies. Moreover, the reductions of system costs by 36.2% and 27.9% when compared to No TS and PreTS, respectively, reveal the economic significance of the robustness granted by PPTS.

Next, with the goal of illustrating the computational advantages of the proposed approach, we have applied three different methods to solve PPTS for the 118-bus system. First, we utilize off-the-shelf branch-and-cut software directly applied to problem (5-1)–(5-16), as done in [33] and [38]. This procedure is hereinafter referred to as BC. The second method is based

Approach	Computing Time (min)	Outer-Loop Iterations
BC	Timeout	–
NCCGA	66.5	12
E-NCCGA	41.2	9

Table 5.3: Impact of Decomposition and Addition of Valid Constraints for the 118-Bus System

on the standard nested CCGA and is denoted by NCCGA. Finally, we have implemented the enhanced nested CCGA, which we denote E-NCCGA.

Table 5.3 lists the computing times required by each approach under the above-described stopping criteria. For the two decomposition-based methods, namely NCCGA and E-NCCGA, the number of outer-loop iterations is also reported. The results evidence that the use of decomposition significantly outperforms the direct application of commercial software, as this moderately-sized multi-period instance is intractable for BC. In addition, the inclusion of valid constraints in the outer-loop master problem not only did substantially decrease the computing time by 38% but also significantly reduced the required number of outer-loop iterations, which is a relevant result for practical application purposes.

Table 5.3 also shows that the proposed E-NCCGA required 41.2 min to attain the high-quality near-optimal solution reported for PPTS. Bearing in mind that a regular computer was used, such a computational effort is acceptable as it is well within the prescribed time frame for day-ahead operation [74–76].

6
Contingency-Constrained Economic Dispatch with Co-Optimized Pre- and Post-Contingency Transmission Switching

In this chapter, we study the effects of considering pre- and post-contingency TS actions in the contingency-constrained ED (CCED) problem to unlock flexible generation resources from the network. More specifically, we focus on the benefits of a smart network capable of performing both preventive and real-time reactive topology changes in response to the occurrence of contingencies. As with the CCUC formulation in Chapter 5, the proposed model ensures the co-optimization of energy and reserves while considering both pre- and post-contingency TS actions, thus producing the optimal policy with transmission flexibility. Furthermore, we consider a multi-period setting with inter-temporal constraints in order to avoid obtaining a suboptimal operation resulting from the non-consideration of future time periods [50].

The resulting multi-period CCED takes the form of a mixed-integer program that features binary recourse decision variables. Hence, in similar fashion to the CCUC case, we propose a novel application of the nested CCGA for CCED. Numerical results from a case study based on an illustrative 4-bus system (see Fig. 5.3) and the IEEE 118-bus system show that the co-optimization of post-contingency TS actions allows unlocking cheap reserves and ramping capabilities at critical periods of the day. As a result, system costs are reduced while also alleviating power imbalance levels by allowing reactive topological adjustments in the transmission network.

6.1
Problem Formulation

The proposed model is cast as a mixed-integer program driven by the minimization of the sum of the offer costs and the worst-case power imbalance cost.

$$\underset{\substack{\theta_{bt}^c,\Phi^w,\Phi_{bt}^{-c},\Phi_{bt}^{+c},\\ f_{lt}^c,p_{it}^c,r_{it}^{dn},r_{it}^{up},z_{lt}^c}}{\text{minimize}} \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}\left[C_{it}^P(p_{it}^0)+C_{it}^{up}r_{it}^{up}+C_{it}^{dn}r_{it}^{dn}\right]+C^I\Phi^w \tag{6-1}$$

subject to:

$$\Phi^w \geq \sum_{b\in\mathcal{B}}\sum_{t\in\mathcal{T}}(\Phi_{bt}^{-c}+\Phi_{bt}^{+c});\ \forall c\in\mathcal{C} \tag{6-2}$$

$$\sum_{i\in\mathcal{I}_b}p_{it}^c+\sum_{l\in\mathcal{L}|to(l)=b}f_{lt}^c-\sum_{l\in\mathcal{L}|fr(l)=b}f_{lt}^c=d_{bt}+\Phi_{bt}^{-c}-\Phi_{bt}^{+c};$$
$$\forall b\in\mathcal{B},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{6-3}$$

$$f_{lt}^c=\frac{A_{lt}^c z_{lt}^c}{x_l}(\theta_{fr(l)t}^c-\theta_{to(l)t}^c);\ \forall l\in\mathcal{L},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{6-4}$$

$$-\overline{F}_l\leq f_{lt}^c\leq\overline{F}_l;\ \forall l\in\mathcal{L},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{6-5}$$

$$z_{lt}^c=1;\ \forall l\in\mathcal{L}\backslash\mathcal{L}^{TS},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{6-6}$$

$$\underline{P}_{it}\leq p_{it}^c\leq A_{it}^c\overline{P}_{it};\ \forall i\in\mathcal{I},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{6-7}$$

$$A_{it}^c(p_{it}^0-r_{it}^{dn})\leq p_{it}^c\leq A_{it}^c(p_{it}^0+r_{it}^{up});\ \forall i\in\mathcal{I},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{6-8}$$

$$0\leq r_{it}^{up}\leq\overline{R}_{it}^{up};\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-9}$$

$$0\leq r_{it}^{dn}\leq\overline{R}_{it}^{dn};\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-10}$$

$$p_{it}^0-p_{it-1}^0\leq RU_i;\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-11}$$

$$p_{it-1}^0-p_{it}^0\leq RD_i;\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-12}$$

$$\Phi_{bt}^{-c}\geq 0,\Phi_{bt}^{+c}\geq 0;\ \forall b\in\mathcal{B},\forall t\in\mathcal{T},\forall c\in\mathcal{C} \tag{6-13}$$

$$z_{lt}^c\in\{0,1\};\ \forall l\in\mathcal{L}^{TS},\forall t\in\mathcal{T},\forall c\in\mathcal{C}. \tag{6-14}$$

The objective function minimized in (6-1) comprises the offered costs of pre-contingency power generation, up- and down-spinning reserve allocation, and the cost induced by the worst-case power imbalance. Constraints (6-2) define the worst-case power imbalance. In (6-3) and (6-4), a dc power flow is modeled, characterizing power balances and line flows, respectively, while taking into account line availability and transmission switching. Line flows are bounded in (6-5) according to the line rated capacities. Non-switchable lines are forced to be switched on by constraints (6-6). In (6-7), power outputs are limited. In (6-8), post-contingency power outputs are bounded by the available reserve contributions. In (6-9) and (6-10), up- and down-spinning reserve contributions are respectively limited. In (6-11) and (6-12), ramping limitations are enforced in the pre-contingency state, as is customary in the related literature [13, 16, 33, 34]. Constraints (6-13) ensure the non-negativity of the variables used in the linearization of the absolute value of the power imbalance. Finally, TS actions are modeled by binary variables in (6-14). Note that, in this formulation, the contingency state $c = 0$ represents the pre-contingency state, wherein all generators and transmission lines are available.

6.2 Equivalent Adjustable Robust Formulation

Similarly to the CCUC problem, the monolithic formulation (6-1)–(6-14) can be recast within an ARO framework, presented in Chapter 3, in the following manner:

$$\underset{\substack{\theta_{bt},\Phi^w,f_{lt},p_{it},\\ r^{dn}_{it},r^{up}_{it},z_{lt}}}{\text{minimize}} \quad \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}\left[C^P_{it}(p_{it}) + C^{up}_{it}r^{up}_{it} + C^{dn}_{it}r^{dn}_{it}\right] + C^I\Phi^w \tag{6-15}$$

subject to:

$$\sum_{i\in\mathcal{I}_b} p_{it} + \sum_{l\in\mathcal{L}|to(l)=b} f_{lt} - \sum_{l\in\mathcal{L}|fr(l)=b} f_{lt} = d_{bt};\ \forall b\in\mathcal{B},\forall t\in\mathcal{T} \tag{6-16}$$

$$-M_l(1-z_{lt}) \le f_{lt} - \frac{1}{x_l}(\theta_{fr(l)t} - \theta_{to(l)t}) \le M_l(1-z_{lt}); \forall l\in\mathcal{L},\forall t\in\mathcal{T} \tag{6-17}$$

$$-z_{lt}\overline{F}_l \le f_{lt} \le z_{lt}\overline{F}_l;\ \forall l\in\mathcal{L},\ \forall t\in\mathcal{T} \tag{6-18}$$

$$z_{lt} = 1;\ \forall l\in\mathcal{L}\backslash\mathcal{L}^{TS},\forall t\in\mathcal{T} \tag{6-19}$$

$$p_{it} - r^{dn}_{it} \ge 0;\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-20}$$

$$p_{it} + r^{up}_{it} \le \overline{P}_{it};\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-21}$$

$$0 \le r^{up}_{it} \le \overline{R}^{up}_{it};\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-22}$$

$$0 \le r^{dn}_{it} \le \overline{R}^{dn}_{it};\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-23}$$

$$p_{it} - p_{it-1} \le RU_i;\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-24}$$

$$p_{it-1} - p_{it} \le RD_i;\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-25}$$

$$z_{lt} \in \{0,1\};\ \forall l\in\mathcal{L},\forall t\in\mathcal{T} \tag{6-26}$$

$$\Phi^w = \underset{\Phi,a_{it},a_{lt}}{\text{maximize}}\left\{\Phi\right. \tag{6-27}$$

subject to:

$$a_{it} \in \{0,1\};\ \forall i\in\mathcal{I},\forall t\in\mathcal{T} \tag{6-28}$$

$$a_{lt} \in \{0,1\};\ \forall l\in\mathcal{L},\forall t\in\mathcal{T} \tag{6-29}$$

$$\boldsymbol{f}(\{a_{it}\}_{i\in\mathcal{I}},\{a_{lt}\}_{l\in\mathcal{L}}) \ge 0;\ \forall t\in\mathcal{T} \tag{6-30}$$

$$\Phi = \underset{\substack{\tilde{\theta}_{bt},\tilde{\Phi}^-_{bt},\tilde{\Phi}^+_{bt},\\ \tilde{f}_{lt},\tilde{p}_{it},\tilde{z}_{lt}}}{\text{minimize}}\left[\sum_{b\in\mathcal{B}}\sum_{t\in\mathcal{T}}\left(\tilde{\Phi}^-_{bt} + \tilde{\Phi}^+_{bt}\right)\right. \tag{6-31}$$

subject to: (6-32)

$$\sum_{i\in\mathcal{I}_b}\tilde{p}_{it} + \sum_{l\in\mathcal{L}|to(l)=b}\tilde{f}_{lt} - \sum_{l\in\mathcal{L}|fr(l)=b}\tilde{f}_{lt} = d_{bt} + \tilde{\Phi}^-_{bt} - \tilde{\Phi}^+_{bt};\ \forall b\in\mathcal{B},\forall t\in\mathcal{T} \tag{6-33}$$

$$- M_l(1 - a_{lt}\tilde{z}_{lt}) \leq \tilde{f}_{lt} - \frac{1}{x_l}(\tilde{\theta}_{fr(l)t} - \tilde{\theta}_{to(l)t}) \leq M_l(1 - a_{lt}\tilde{z}_{lt});$$

$$\forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (6\text{-}34)$$

$$- a_{lt}\tilde{z}_{lt}\overline{F}_l \leq \tilde{f}_{lt} \leq a_{lt}\tilde{z}_{lt}\overline{F}_l; \ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (6\text{-}35)$$

$$a_{it}(p_{it} - r_{it}^{dn}) \leq \tilde{p}_{it} \leq a_{it}(p_{it} + r_{it}^{up}); \ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \quad (6\text{-}36)$$

$$\tilde{z}_{lt} = 1; \ \forall l \in \mathcal{L} \backslash \mathcal{L}^{TS} \quad (6\text{-}37)$$

$$\tilde{\Phi}_{bt}^{-} \geq 0, \tilde{\Phi}_{bt}^{+} \geq 0; \ \forall b \in \mathcal{B}, \forall t \in \mathcal{T} \quad (6\text{-}38)$$

$$\tilde{z}_{lt} \in \{0, 1\}; \ \forall l \in \mathcal{L}, \forall t \in \mathcal{T} \quad (6\text{-}39)$$

$$\left.\left.\tilde{p}_{it} \geq 0; \ \forall i \in \mathcal{I}, \forall t \in \mathcal{T} \right]\right\}. \quad (6\text{-}40)$$

As discussed in Chapter 3, this trilevel problem is suitable for the application of the nested CCGA.

6.3 Solution Methodology

In this section, we present the solution methodology based on the nested CCGA utilized to solve the multi-period CCED. As with the CCUC, the proposed methodology comprises two loops that are iterated until convergence.

6.3.1 Outer Loop

The outer loop embodies a master-oracle framework that is iterated until convergence to determine the solution of problem (6-1)–(6-14). It converges once the bounds provided by the master problem and the oracle problem are within a pre-specified tolerance ϵ^o.

6.3.1.1 Master Problem

The master problem is a relaxation of the original problem (6-1)–(6-14) where, at each outer-loop iteration k, $\mathcal{C}$ is replaced with a subset of k contingency states. At each iteration k, solving the master problem outputs decisions $p_{it}^{0(k)}$, $r_{it}^{up(k)}$, and $r_{it}^{dn(k)}$, which represent the optimal schedule for the subset of k contingency states considered. Thus, its solution allows deriving a lower bound for the optimal value of the objective function (6-1):

$$LB^{(k)} = \sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} \left[C_{it}^{P}(p_{it}^{0(k)}) + C_{it}^{up} r_{it}^{up(k)} + C_{it}^{dn} r_{it}^{dn(k)} \right] + C^{I} \Phi^{w(k)}. \quad (6\text{-}41)$$

6.3.1.2
Oracle Problem

The oracle problem identifies the worst-case contingency state with respect to the solution given by the preceding master problem. It is formulated as a bilevel problem wherein the upper level is responsible for finding the contingency state that maximizes power imbalance, while the lower level obtains the optimal system reaction.

Note that, since the oracle problem comprises the identification of the worst-case contingency through a security criterion and the generation redispatch, thus not including the scheduling of generators, the oracle problem for the CCED is identical to the one utilized for CCUC, i.e., problem (5-50)–(5-61).

At each outer-loop iteration k, the following upper bound for the optimal cost can be derived:

$$UB^{(k)} = \sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} \left[C_{it}^{P}(p_{it}^{0(k)}) + C_{it}^{up} r_{it}^{up(k)} + C_{it}^{dn} r_{it}^{dn(k)} \right] + C^{I} \Phi^{(k)}. \tag{6-42}$$

6.3.1.3
Inner Loop

Since the oracle problem for CCED is identical to the one used for CCUC, the inner CCGA loop utilized to solve it is also identical to the one presented in Section 6.3.1.3.

6.4
Numerical Results

In order to investigate the benefits and effects of co-optimized pre- and post-contingency TS for CCED, numerical simulations were conducted over the same two systems analyzed in Section 5.4. In this case, we consider time periods of 15 minutes and our goal is to solve the CCED for the following four time periods (i.e., the following hour) at each hour of the day. The daily load curve utilized in the numerical simulations is displayed in Fig. 6.1. It represents a typical load curve with peaks at around 10:00 and 19:00.

As in Section 5.4, we compare the results obtained with formulations considering no TS, only pre-contingency TS, and co-optimized pre- and post-contingency TS. These formulations are once again dubbed No TS, PreTS, and PPTS, respectively. The nested CCGA described in Section 6.3 was employed to address PPTS, while No TS and PreTS were solved through a standard single-loop CCGA. The sets of switchable lines utilized were the same as in

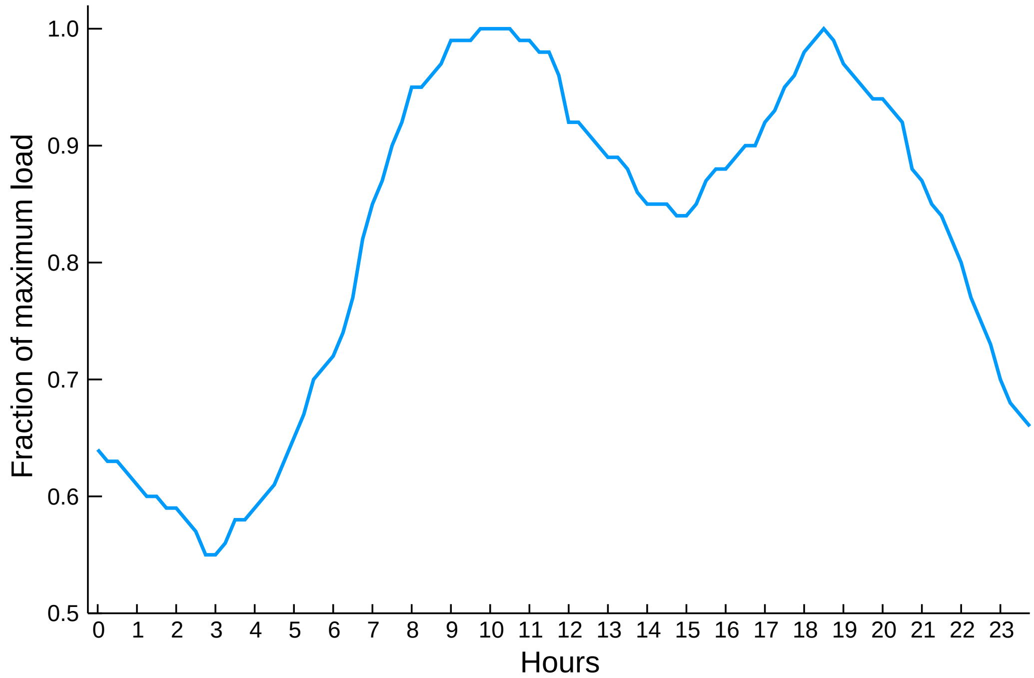

Figure 6.1: Daily load curve considered in the numerical simulations.

Time Period		No TS	PreTS	PPTS
03:00–04:00	System Cost ($)	38,953.2	38,953.2	38,953.2
	Φ^w (%)	0.0	0.0	0.0
10:00–11:00	System Cost ($)	190,529.2	131,154.3	68,468.4
	Φ^w (%)	24.1	12.2	0.0
22:00–23:00	System Cost ($)	97,394.0	83,442.0	52,338.0
	Φ^w (%)	11.7	7.9	0.0

Table 6.1: Impact of Post-Contingency TS on Solution Quality for Different Periods of the Day for the 4-Bus System

Section 5.4 for both systems. The execution of the decomposition procedures was stopped when a solution was found within a 1% optimality tolerance. The system data utilized is available in [77]. All tests were conducted utilizing the Julia language and CPLEX 12.8 on an Intel Core i7-490K processor at 4.00 GHz and 32 GB of RAM.

6.4.1 4-Bus Example

For the 4-bus illustrative system, we compare the three formulations at three distinct periods of the day: 03:00–04:00, when the demand is at its lowest point, 10:00–11:00, when the demand is at its peak, and 22:00–23:00, when the demand is at an average level. The results are displayed in Table 6.1.

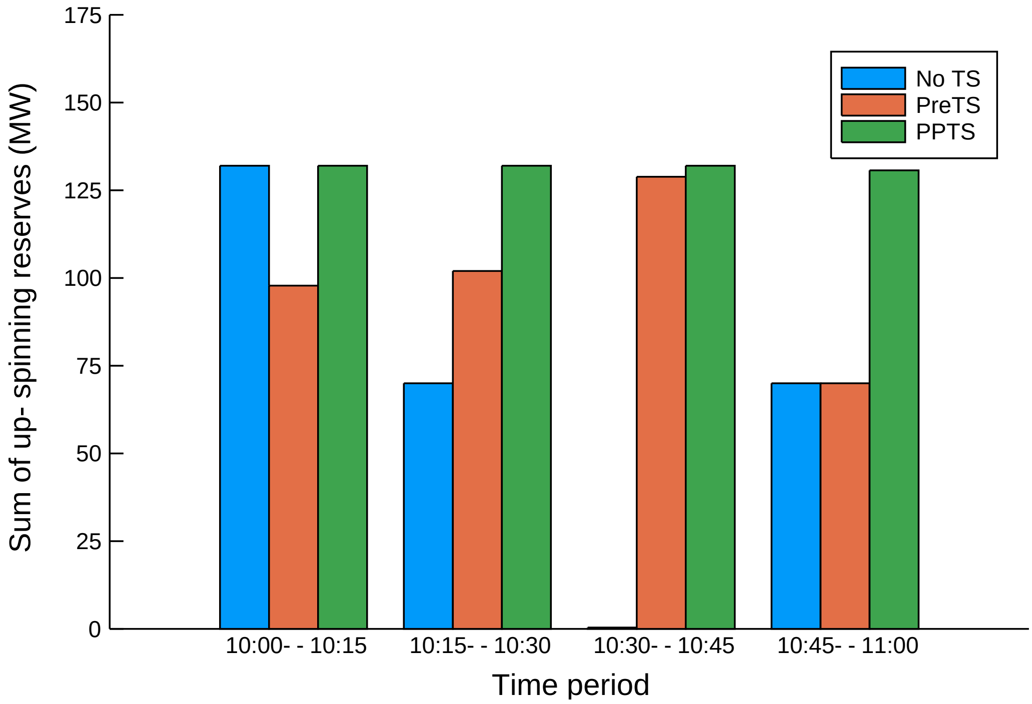

Figure 6.2: Sum of up-spinning reserve allocations for the 4-bus system in the 10:00–11:00 period.

It can be seen that, for the period when the demand is at its lowest point, TS has no effect on the solution quality. When the demand is higher, PreTS does decrease the worst-case power imbalance levels, but they are still significant. PPTS, on the other hand, is capable of nullifying the worst-case power imbalance in all cases. The 10:00–11:00 period of this illustrative example, in particular, represents an extreme case where disregarding TS leads to a power imbalance level of over 24%, while considering PPTS assures a 0% worst-case power imbalance under the $n-1$ criterion. This example, while not realistic, evidences the potential of PPTS to improve system reliability.

Additionally, Fig. 6.2 displays the sum of up-spinning reserve allocations in the critical 10:00–11:00 period for each formulation. It is visible that PPTS significantly modifies the reserve allocations, unlocking reserve capabilities that were inhibited due to electrical constraints.

6.4.2
118-Bus System

For the 118-bus system, we have investigated the resulting operation for all 24 hours of the day. Figs. 6.3 and 6.4 depict the system costs for the 118-bus system for No TS, PreTS and PPTS in each hour. It can be seen in the figures that, in the periods when the demand was low, the three formulations resulted in similar system costs. However, in the periods when the system was under

Hours	0	1	2	3	4	5	6	7	8	9	10	11
Time (s)	96	77	72	102	116	94	71	54	87	41	127	74
Hours	12	13	14	15	16	17	18	19	20	21	22	23
Time (s)	46	48	77	54	106	92	57	81	92	45	108	87

Table 6.2: Computing Times for the Contingency-Constrained Economic Dispatch for the 118-Bus System

stress, PPTS obtained significant cost savings when compared to No TS and PreTS. This is also a direct consequence of the results displayed in Figs. 6.5 and 6.6, which show the worst-case power imbalance levels in terms of system load in each hour of operation. While PPTS had a 0% worst-case power imbalance in all time periods, No TS and PreTS displayed power imbalance levels of up to 1.6% and 0.5%, respectively.

In terms of computational performance, PPTS was run in an average time of 79.4 s, with the highest computing time being 127 s. These results are well within the required time frame for operation in a 15-minute window discretization. The computing times for each hour are exposed in Table 6.2.

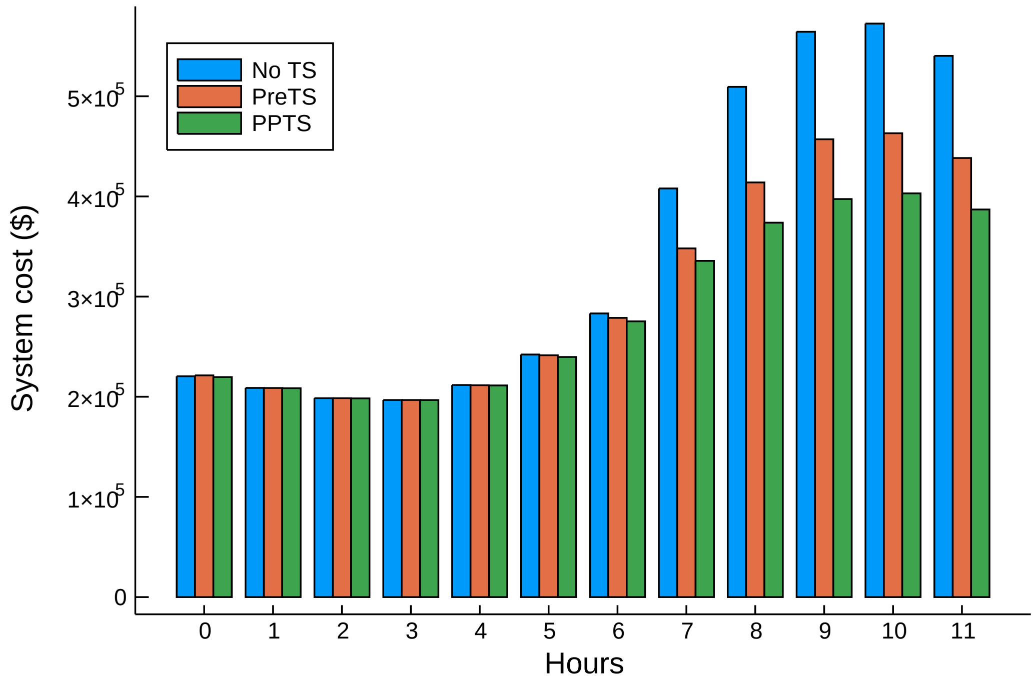

Figure 6.3: System costs for the 118-bus system during the first half of the day.

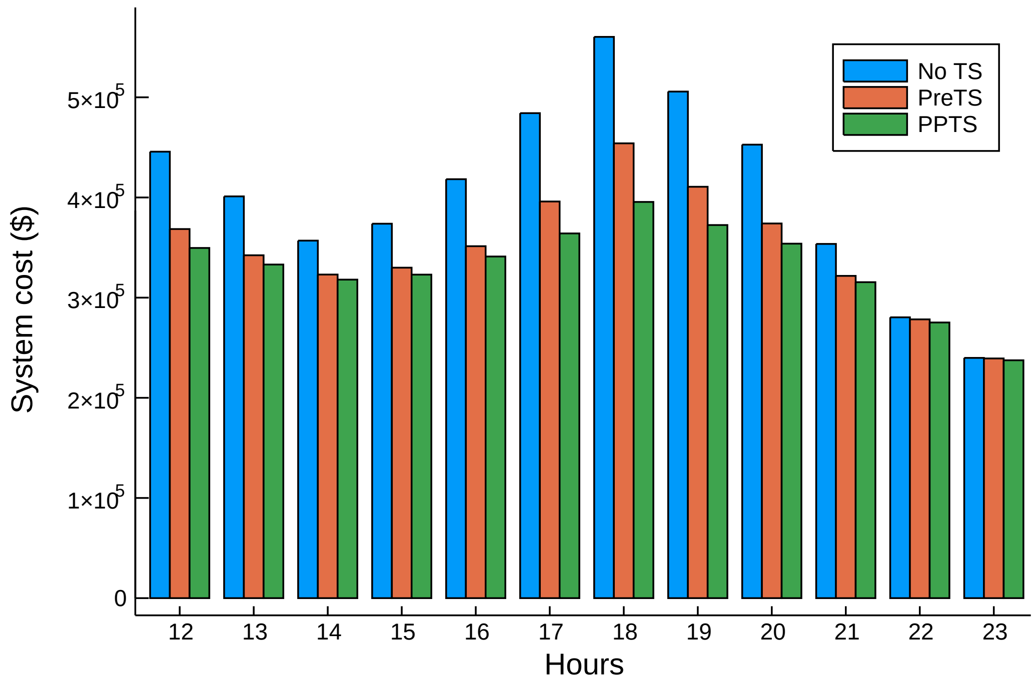

Figure 6.4: System costs for the 118-bus system during the second half of the day.

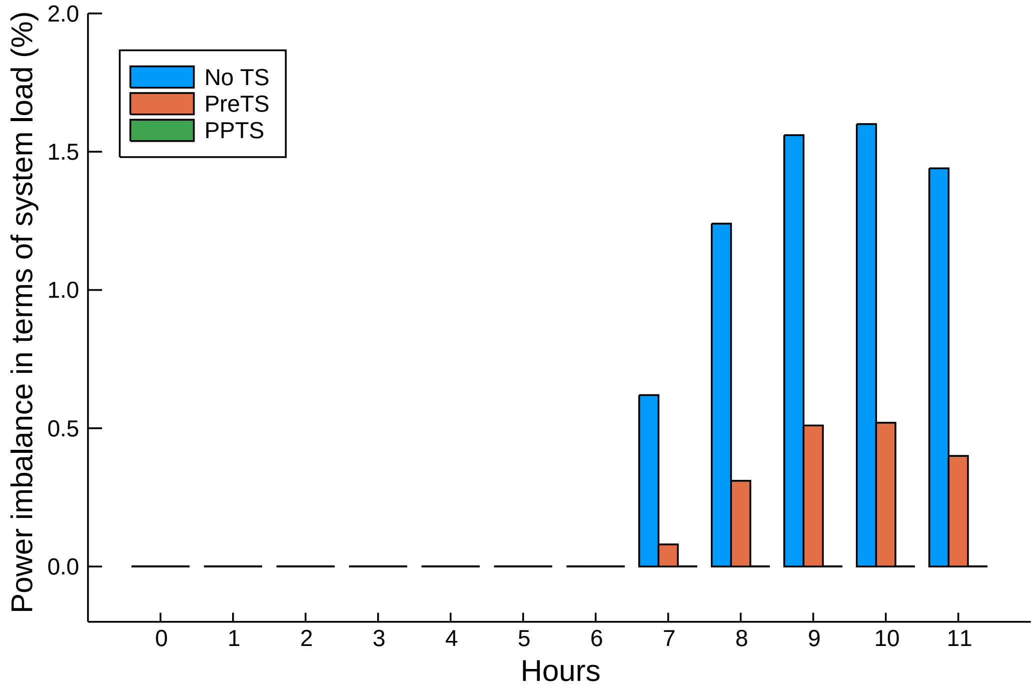

Figure 6.5: Worst-case power imbalance levels in terms of system load for the 118-bus system during the first half of the day.

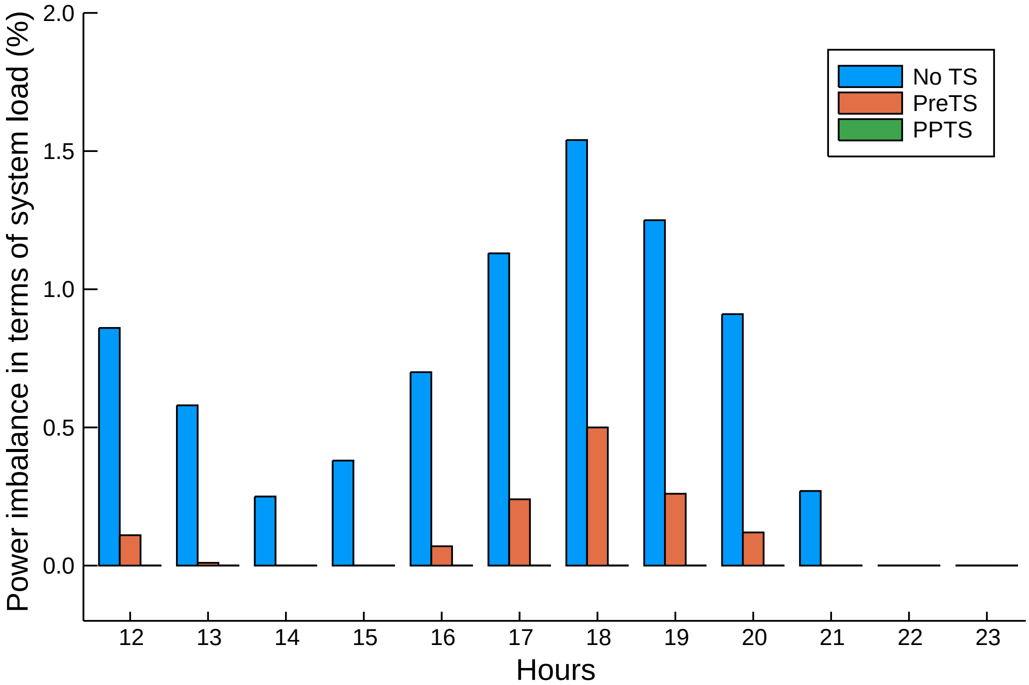

Figure 6.6: Worst-case power imbalance levels in terms of system load for the 118-bus system during the second half of the day.

7
Conclusion

This work has addressed the contingency-constrained unit commitment and economic dispatch with the co-optimization of energy, reserves, as well as pre- and post-contingency transmission switching. For the first time in the literature, all the aforementioned features have been considered in a multi-period setting. Solution methodologies presented in the related literature fail to address the post-contingency binary variables, and straightforwardly solving the proposed formulation for contingency-constrained unit commitment with off-the-shelf commercial software exceeds current computing capabilities even for moderately-sized instances.

To address these issues, the proposed monolithic formulations are recast within an adjustable robust optimization framework, and an exact decomposition method based on the nested column-and-constraint generation algorithm is applied. The solution methodology involves an outer loop wherein the original problem is decomposed into a master-oracle structure. The resulting bilevel oracle problem is responsible for obtaining the contingency state yielding the largest power imbalance for a given schedule. The presence of lower-level binary variables in the oracle problem is handled by an inner loop involving an inner master problem and an inner subproblem. Additionally, the computational performance of the standard nested column-and-constraint generation algorithm is improved for the contingency-constrained unit commitment by the incorporation of a set of valid constraints. Moreover, the novel formulations and solution methodologies proposed in this work allow conducting numerical simulations that were previously not possible or computationally infeasible.

The reported numerical experience allows drawing five main conclusions.

1. The incorporation of co-optimized post-contingency transmission switching to unit commitment and economic dispatch formulations benefits system operation by consistently reducing system costs and decreasing power imbalance levels in the worst contingency states when the system is under stress.

2. The cost savings and decreases in power imbalance levels are a consequence of a significantly different pre-contingency schedule when post-

contingency switching is co-optimized. The differences when compared to formulations considering solely pre-contingency switching include reserve contributions and line statuses.

3. From a computational perspective, the proposed solution technique significantly outperforms the direct application of off-the-shelf commercial software adopted in previous related works.

4. The computational effort required to attain high-quality near-optimal solutions is within industry standards for a medium-scale benchmark such as the IEEE 118-bus system, both for the contingency-constrained unit commitment within a day-ahead setting and for the contingency-constrained economic dispatch within a 15-minute time window considering one hour ahead.

5. For the contingency-constrained unit commitment, the computational advantage of the proposed enhancement in the nested column-and-constraint generation algorithm is backed by the substantial reduction in both the computing time and the number of outer-loop iterations that are required for convergence.

We believe this work motivates several possible future avenues of research. First, the possibility of developing more tailored algorithms in order to tackle the master problem, which iteratively grows and becomes extremely computationally costly to solve. Second, the consideration of co-optimized corrective switching within planning problems such as system expansion. Finally, the adaptation of the models and techniques utilized in this work to AC formulations.

A
Nomenclature

The symbols used in Chapters 5 and 6 are defined in this section. Superscript "m" is used to represent new variables in the inner master problem. Superscripts "(k)" and "(m)" are used to denote the value of a variable at outer-loop iteration k and inner-loop iteration m, respectively.

Sets and Indices

$\mathcal{B}$	Set of bus indices b.
$b(i)$	Bus where generator i is located.
$\mathcal{C}$	Set of contingency state indices c. The pre-contingency state is represented by $c = 0$.
$\mathcal{C}_k$	Set of contingency state indices c considered at outer-loop iteration k.
$\mathcal{F}_i$	Feasibility set for the decision variables associated with generator i.
$fr(l)$	Origin bus index of line l.
$\mathcal{I}$	Set of generator indices i.
$\mathcal{I}_b$	Set of indices i of generators located at bus b.
$\mathcal{L}$	Set of transmission line indices l.
$\mathcal{L}^{TS}$	Set of indices l of switchable transmission lines.
$\mathcal{T}$	Set of time period indices t.
$to(l)$	Destination bus index of line l

Functions

$C^P_{it}(\cdot)$	Production cost function offered by generator i in period t.
$\boldsymbol{f}(\cdot)$	Vector of linear functions defining the set of contingency states.

Parameters

ϵ^i, ϵ^o	Inner- and outer-loop convergence parameters.
A^c_{it}	Parameter that is equal to 1 if generator i is available in period t under contingency state c, being 0 otherwise.
A^c_{lt}	Parameter that is equal to 1 if transmission line l is available in period t under contingency state c, being 0 otherwise.
C^I	Cost coefficient of power imbalance.
C^{dn}_{it}, C^{up}_{it}	Down- and up-spinning reserve costs offered by generator i in period t.
d_{bt}	Power demand at bus b in period t.
$\overline{F}_l$	Rated capacity of transmission line l.
K	Number of unavailable system components.
LB, UB	Lower and upper bounds for the total cost.
M_l	Big-M parameter related to transmission line l.
$\underline{P}_{it}, \overline{P}_{it}$	Lower and upper production limits of generator i in period t.
$\overline{R}^{dn}_{it}, \overline{R}^{up}_{it}$	Maximum down- and up-spinning reserve contributions of generator i in period t.
RD_i, RU_i	Ramp-down and ramp-up limits of generator i.
SD_i, SU_i	Shutdown and start-up ramp limits of generator i.
x_l	Reactance of line l.

Decision Variables

$\theta_{bt}^{c}, \tilde{\theta}_{bt}$ Phase angles at bus b in period t under contingency state c and in the lower level of the oracle problem.

λ_t, ξ_{it} Auxiliary variables used in the valid constraints.

Φ, Φ^{ap} Levels of system power imbalance resulting from the oracle problem and the inner master problem.

Φ^{w} Worst-case system power imbalance.

$\Phi_{bt}^{-c}, \Phi_{bt}^{+c}$ Variables used in the linearization of the absolute value of the power imbalance at bus b in period t under contingency state c.

$\tilde{\Phi}_{bt}^{-}, \tilde{\Phi}_{bt}^{+}$ Variables used in the linearization of the absolute value of the power imbalance at bus b in period t in the lower level of the oracle problem.

a_{it} Binary variable that is equal to 1 if generator i is available in period t, being 0 otherwise.

a_{lt} Binary variable that is equal to 1 if transmission line l is available in period t, being 0 otherwise.

c_{it}^{sd}, c_{it}^{su} Shutdown and start-up costs of generator i in period t.

$f_{lt}^{c}, \tilde{f}_{lt}$ Power flows of line l in period t under contingency state c and in the lower level of the oracle problem.

$p_{it}^{c}, \tilde{p}_{it}$ Power outputs of generator i in period t under contingency state c and in the lower level of the oracle problem.

p^{w} Worst-case system production.

r_{it}^{dn}, r_{it}^{up} Down- and up-spinning reserve contributions of generator i in period t.

v_{it} Binary variable that is equal to 1 if generator i is scheduled in period t, being 0 otherwise.

$z_{lt}^{c}, \tilde{z}_{lt}$ Binary variables that are equal to 1 if transmission line l is switched on in period t, being 0 otherwise, under contingency state c and in the lower level of the oracle problem.

Dual Variables

β_{bt} Dual variable associated with the power balance equation at bus b in period t in the lower level of the oracle problem.

γ_{it}, χ_{it} Dual variables associated with the constraints imposing lower and upper bounds for $\tilde{p}_{it}$.

π_{lt}, σ_{lt} Dual variables associated with the constraints imposing lower and upper bounds for $\tilde{f}_{lt}$.

ω_{lt}, ζ_{lt} Dual variables associated with the constraints relating power flows and phase angles for line l in period t in the lower level of the oracle problem.

B
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