A Model-based Parameter Space in Monte Carlo Simulations for European Short-term Adequacy Assessments

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***Abstract*—The Short-Term Adequacy (STA) assessment is crucial for raising risk awareness among stakeholders and aiding European system operations in quickly identifying potential risks. To calculate cross-border exchange capacities in European STA assessments, the flow-based (FB) approach is used to define the parameter space in Monte Carlo simulations. However, Transmission System Operators (TSOs) currently rely on data-driven methods to define the FB domain. These methods necessitate extensive historical data on import-export capacities, which may not always align with Monte Carlo samples. Issues related to Energy Not Served (ENS) can arise even when Monte Carlo samples are aligned with the FB domain. To address these challenges, this paper introduces an analytical model based on parametric programming. This model maps the decision variables to zonal total loads, ensuring a more accurate parameter space in Monte Carlo simulations, and is free from ENS issues. Additionally, the model proactively adjusts the ENS index to reflect the parameter space under specific ENS conditions, thereby enhancing the generation of accurate Monte Carlo scenarios for subsequent STA assessments.**

Keywords—Cross-border exchange capacities, Flow-based market coupling, Monte Carlo simulation, Parametric programming, Short-term adequacy assessments.

I. Introduction

Adequacy assessments, especially in the short term, are becoming increasingly vital to prevent and manage potential electricity crises [1]. Short-term adequacy (STA) assessments play a critical role in determining whether electric power systems can meet future load demands under varying operational conditions. At the same time, the transition towards decarbonizing the electricity sector, coupled with the integration of renewable sources, relies heavily on cross-border cooperation. To facilitate energy sharing across different zones (countries), it is also essential to maximize the use of the interconnections.

The regional STA assessments provide the capability to pinpoint potential electricity adequacy shortfalls, whether within specific load-control areas or on a wider, pan-European scale. The primary objective of STA assessments is to raise risk awareness among stakeholders, as well as to support system operations by identifying and timing adequacy risks [1][2]. Beyond risk identification, these assessments play a pivotal role in system operation, providing critical insights that guide actions, such as maintenance scheduling, to mitigate potential risks.

The regional STA assessments consider possible cross-border exchange capacities and operational security limits. Typically, they employ either deterministic or probabilistic methods [3]. The deterministic approach aligns peak load demands with available generation, identifying capacity surpluses or deficits. On the other hand, the probabilistic approach, utilizing Monte Carlo simulations, accounts for inherent uncertainties in load and generation, enabling a more comprehensive analysis [3][4].

The Flow-Based (FB) approach, incorporating cross-border exchange capacities within Europe's electricity network, has emerged as the preferred model. Primarily, the FB approach endeavors to explicitly and directly represent the network limitations within market clearing processes, thereby facilitating energy exchanges across different bidding zones [5]. This approach, initially implemented in the Central Western Europe (CWE) region in 2015 [6], is on track for expansion to 13 countries in the CORE region [7]. It operates by considering the available capacities of the zonal network, forming a polytope for potential cross-border exchanges.

References [8]-[10] elaborate on the construction of the FB domain and its impact on Flow-Based Market Coupling (FBMC) results. Following the practical application of FBMC in 2019, European regulations required the integration of the Flow-Based (FB) approach into European STA assessments, wherever it was applicable [11]. This integration profoundly influences interconnected electric power networks. However, determining cross-border exchange capacities via FB domains presents a substantial challenge, especially when trying to accurately capture potential restrictive transmission constraints under the current system conditions.

European market data [12] reveals the significant fluctuations in cross-border exchange capacities, highlighting their profound impact on the outcomes of adequacy assessments. Regional adequacy assessments become important, especially when triggered by the results of STA Cross-Regional assessments or upon TSO request (e.g., in cases of regional scarcity or insufficient cross-zonal capacities). CWE region TSOs opt for the Antares simulator to conduct probabilistic adequacy assessments, utilizing Monte Carlo scenarios generated from the characteristics of the polytope. A critical prerequisite for realizing a realistic and accurate STA is the precise definition of the FB domain. This ensures its seamless alignment with each Monte Carlo scenario generated for the probabilistic adequacy assessments. Practically, the commercial software, exemplified by the Antares simulator employed by CWE TSOs, is advised to incorporate functionality to dynamically update the FB domain for each Monte Carlo sample [13][14].

Currently, several European TSOs, including European Network of TSO (ENTSO-E) [15], French TSO (RTE) [16], and Belgian TSO (Elia) [17], have adopted a data-driven approach for the FB domains. This method entails historical FB domain data, integrating it with a clustering technique applied to Monte Carlo sampling. The goal is to accurately match cluster representatives of FB domain with working states in the adequacy studies. However, a significant challenge arises due to the diverse shapes and forms that FB domains can take. A single cluster representative struggles to encapsulate the physical properties of all FB domains within its group, leading to potential inaccuracies. As a result, even if the Monte Carlo samples match the FB domain well, the Energy Not Served (ENS) issue can still occur. These inaccuracies, if not addressed, hold the risk of compromising the precision of subsequent STA assessments [7].

This paper introduces a parametric programming model to provide a parameter space in Monte Carlo simulations with current FB domains. Our contributions are twofold:

1) Accuracy: The proposed model establishes a clear and precise relationship between external factors and generation, achieving a polytope of zonal total loads based on the net positions' polytope from FB domains. The new polytope indicates a more accurate parameter space in Monte Carlo simulations. Moreover, it can adjust parameter space in Monte Carlo simulations to reflect specific ENS conditions and align it with the generated Monte Carlo scenario.

2) Scalability: This model requires current conditions such as the availability of generation capacities, the expected total load, and the remaining available margins from the TSOs. All these conditions can be determined in advance within the European market framework. Furthermore, the design supports other market frameworks, easily adapting to changes in zonal network components and integrating new conditions with the introduction of additional variables.

II. Flow-based Domains and Adequancy Assessments

At a given hour, the FB domain is defined by a set of linear constraints on the network elements using a data-driven method, which forms a polytope representing the net positions of different zones [8]. This polytope is integrated into the STA assessments, which is a variant of economic dispatch [19].

A. Flow-based Domains from Linear Constraints

Accounting for the interaction of flows across diverse zones, the FBMC effectively models feasible power exchanges related to cross-zonal electricity trades. A critical distinction to be recognized lies in the discrepancy between commercial trades and actual physical flows. This discrepancy indicates that the electricity exchange between two market zones cannot be exclusively dedicated to their commercial trades. Instead, a part of this capacity is invariably utilized by flows stemming from the trades occurring in other market zones [18][19]. Therefore, a polytope is required to reflect the capacities of multiple TSOs and their control areas, rather than focusing solely on their bilateral trades.

Assuming that there are *I* distinct zones involved in the FBMC, the data-driven method systematically constructs an *I*-dimensional polytope to represent the FB domain. This polytope characterizes the feasible capacities for cross-zonal exchanges, taking into account both physical and critical network elements. Generally, it can be formulated from the historical FB domain, as well as from load and generation databases. These constraints are then linearly approximated, resulting in variants of the network constraints described below.

$$\mathbf{S}\times\mathbf{F}\le\mathbf{R} \tag{1}$$

where $\mathbf{S}$ is a matrix of power transfer distribution factors (PTDF). $\mathbf{F}$ is a net position vector of all zones, which refers to the electricity export minus import. $\mathbf{R}$ is the vector of the Remaining Available Margin (RAM) of the network elements.

Constraints (1) serve to define the limits of feasible cross-zonal exchanges, employing a linear approximation of the physical network constraints. This is crucial to ensure that fluctuations in the net position of different zones do not violate the RAM on chosen network elements. Each individual row within constraints (1) delineates a half-space of the polytope, collectively forging an approximated polytope. The vertices of this FB domain polytope, in turn, demarcate the boundary conditions of extreme exchanges between each country and its counterparts in the CWE region.

The net position's polytope is significantly influenced by the parameters of PTDF and RAM. The RAM is calculated as the maximum flow minus the flow in the base case, which includes long-term capacities and the flow reliability margin [20][21]. The 'base case' represents the most reliable forecast of operational conditions for the targeted horizon, determined under specific conditions [5]. For the day-ahead scheduling, this 'base case' is typically based on forecasts made two days prior to the assessment of the electricity system [7]. Consequently, the FB approach ensures that the power flows for cross-zonal exchanges, which are physically permissible, are determined through a set of linear constraints and a corresponding polytope.

B. Adequancy Assessments with Flow-based Domains

Based on the FB domains and external factors (the availability of generation capacities and the expected total loads), the adequacy assessment model is developed in [5][19] as a variant of economic dispatch for all zones.

$$\min_{G_i,E_i}\sum\nolimits_{i=1}^{I}\left(C_i^G G_i + C_i^E E_i\right) \tag{2}$$

$$s.t.\qquad F_i = G_i - D_i + E_i, \forall i\in I \tag{3}$$

$$G_i^{\min}\le G_i\le G_i^{\max}, \forall i\in I \tag{4}$$

$$0\le E_i\le E_i^{\max}, \forall i\in I \tag{5}$$

$$\sum\nolimits_{i=1}^{I} F_i = 0 \tag{6}$$

$$\mathbf{S}\times\mathbf{F}\le\mathbf{R} \tag{7}$$

$$\mathbf{G}\in\mathbb{R}^I, \mathbf{E}\in\mathbb{R}^I \tag{8}$$

where E_i and G_i are decision variables. G_i denotes the aggregated generation of zone i. E_i is zonal ENS of zone i. C_i^G is the cost of generation production for zone i. C_i^E is the cost incurred from ENS-related issues for zone i. D_i gives the expected load demand (aggregated) of zone i and F_i stands for the net position of zone i, which refers to the electricity export minus import. The superscripts min/max represent the minimum/maximum bound of variables. $\mathbf{G}$ is a vector of zonal generation and $\mathbf{E}$ is a vector of zonal ENS.

The objective function (2) aims to minimize the total amounts of generation costs and ENS costs. Constraints (3) ensure that the sum of generation G_i, load D_i and ENS E_i is equal to net position F_i in each zone. To ensure the feasible results of the optimization problem, the slack variable E_i is introduced to address the generation shortage of each zone. Constraints (4) establish upper and lower bounds for the production of zonal generation. Constraints (5) guarantee the non-negative values of the ENS and set an upper limit. Constraint (6) expresses the sum of net positions is balanced in the interconnection system. Constraints (7) integrate the FB domains into the adequacy assessment. According to the constraints (3), net positions can be converted into decision variables in the optimization problem.

The adequacy assessment model (2)-(8) relies on Monte Carlo sampling of external factors, such as the availability of generation capacities and the expected total loads in different zones. Since constraints (7) limit the potential for cross-border exchanges, the final results must fit within the FB domain's polytope. Under no ENS conditions, the parameter space for Monte Carlo simulations should be more restrictive than the FB domain's polytope.

The inaccuracy of the parameter space could drastically alter the final adequacy results. This distortion arises because the FB domain's polytope often represents a broader range of possibilities than what actually exists. As a result, even when external factors completely align with the pre-defined FB domains, Monte Carlo sampling may still produce scenarios with non-zero ENS. To address this issue, the application must update the parameter space in Monte Carlo simulations to accurately reflect scenarios where ENS occurs. This alignment between the parameter space and Monte Carlo sampled scenarios is vital for a risk-based STA assessment, as it ensures more precise and reliable results.

III. Parameter Space in Monte Carlo Simulation

The Monte Carlo sampling process assesses various external factors, including the availability of generation capacities and the expected total loads in different zones. Practically, the TSO of each zone needs to provide necessary information (availability of generation capacities, expected total loads and operational security limits). The STA industrial tool, also known as the Pan-European or Cross-Regional tool, gathers this information [22]. However, the polytope of net positions, defined by constraints (1), is unable to distinguish between results that produce ENS and those that do not. This is because the accurate parameter space is defined by not only constraints (1) but also the other constraints in the model (2) -(8). As discussed in Section II.B, it is crucial to update the parameter space in Monte Carlo simulations to align with the external factors.

A. Parametric Programming Model for Zonal Total Loads

According to constraints (3), the net position F_i of zone i is defined by the aggregated generation G_i, the expected total load D_i, and the zonal ENS E_i. It is important to note that G_i and E_i are decision variables in model (2)-(8), and as such, their values depend on the value of the expected total load D_i. Given specific values of expected total load D_i, model (2)-(8) can optimize G_i and E_i. Under the current optimal solution, model (2)-(8) can then calculate the net position F_i.

When different values of the expected total load D_i are selected, the optimization problem has the same linear formulation. When all expected total loads are treated as programming parameters—referred to as zonal total loads in this paper—the problem transforms into a parametric programming problem. To distinguish between them, we add the superscript P to represent the parameters of zonal total loads in the parametric programming model.

Prevailing European STA assessments evaluate the electric power system's capacity to meet the total load demand from a perspective of day-ahead scheduling [15][23]. In this context, we strategically select the zonal total loads as programming parameters, thereby effectively representing the parameter space in the Monte Carlo simulations through a comprehensive polytope of zonal total loads.

The parametric programming model is formulated as below.

$$\min_{G_i, E_i} \sum_{i=1}^{I} \left(C_i^G G_i + C_i^E E_i \right) \tag{9}$$

$$s.t. \quad F_i = G_i - D_i^P + E_i, \forall i \in I \tag{10}$$

$$G_i^{\min} \le G_i \le G_i^{\max}, \forall i \in I \tag{11}$$

$$0 \le E_i \le E_i^{\max}, \forall i \in I \tag{12}$$

$$\sum_{i=1}^{I} F_i = 0 \tag{13}$$

$$D_i^{\min} \le D_i^P \le D_i^{\max}, \forall i \in I \tag{14}$$

$$\mathbf{S} \times \mathbf{F} \le \mathbf{R} \tag{15}$$

$$\mathbf{G} \in \mathbb{R}^I, \mathbf{E} \in \mathbb{R}^I, \mathbf{D}^P \in \mathbb{R}^I \tag{16}$$

where the $\mathbf{D}^P$ is a vector of zonal total loads as programming parameters.

With the given zonal total loads, the model (2)-(8) aims to find the optimal values $\mathbf{G}$ and $\mathbf{E}$ from a set of feasible solutions. When the parameters of this optimization problem change, such as the zonal total loads $\mathbf{D}^P$, the parametric programming model (9)-(16) provides information on how the optimal solutions $\mathbf{G}$ and $\mathbf{E}$ change in response to varying parameters $\mathbf{D}^P$. The relationship between the varying parameters $\mathbf{D}^P$ and decision variables $\mathbf{G}$ and $\mathbf{E}$ will be detailed later.

In the parametric programming problem, another key consideration is the range of values of $\mathbf{D}^P$. The parameter bounds of $\mathbf{D}^P$ impose restrictions on the values that the parameters can take, thereby affecting the feasible region and the optimal solution of the optimization problem. In this paper, these bounds are determined by external factors related to the physical problem, including the availability of generation capacities $G_i^{\max}$ and the expected total loads D_i (from predictions) in different zones. The external factors determine the maximum export capacities by $G_i^{\max}$ and the maximum import capacities by D_i, which in turn define the practical range of net position for zone i. Therefore, the potential range of net position F_i in zone i should vary between $[-D_i,\ G_i^{\max}]$ before solving the problem. Correspondingly, the bounds of D_i^P in this problem are set to $[0,\ D_i + G_i^{\max}]$, and thus, constraints (14) are formulated.

B. Parametric Solution and Net Positions

With the parametric programming model (9)-(16), the decision variables **G** and **E** can be expressed as piecewise affine functions of the programming parameter $\mathbf{D}^P$. Then, the vector of net positions **F** can also be represented by piecewise affine functions of programming parameter $\mathbf{D}^P$.

Initially, the parametric solution serves to map programming parameters directly into decision variables. In situations dealing with a parametric linear problem, this map takes the form of a piecewise affine function as below.

$$\begin{bmatrix} \mathbf{G}_m^* \\ \mathbf{E}_m^* \end{bmatrix} = \begin{bmatrix} \mathbf{u}_m^G \\ \mathbf{u}_m^E \end{bmatrix} \mathbf{D}^P + \begin{bmatrix} \mathbf{v}_m^G \\ \mathbf{v}_m^E \end{bmatrix},\ if\ \mathbf{D}^P \in H_m \tag{17}$$

where $\mathbf{u}_m^G$, $\mathbf{u}_m^E$, $\mathbf{v}_m^G$ and $\mathbf{v}_m^E$ are the m-th affine coefficients, which calculate the decision variables $\mathbf{G}^*$ and $\mathbf{E}^*$ when $\mathbf{D}^P$ resides in the m-th polytope H_m. Due to the fact that $\mathbf{D}^P$, $\mathbf{G}^*$, $\mathbf{E}^*$ are all $I\times1$ vectors, the affine coefficients $\mathbf{u}_m^G$ and $\mathbf{u}_m^E$ are $I\times I$ matrices while $\mathbf{v}_m^G$ and $\mathbf{v}_m^E$ are $I\times1$ vectors.

By introducing the affine function (17) into the constraints (10)-(15), we can categorize the constraints into active and inactive sets, resulting in the parametric constraints $\mathbf{A}_m\mathbf{D}^P \leqslant \mathbf{b}_m$. The m-th polytope H_m is defined below.

$$H_m = \left\{ \mathbf{D}^P \in \mathbb{R}^I : \mathbf{A}_m \mathbf{D}^P \le \mathbf{b}_m \right\} \tag{18}$$

where $\mathbf{A}_m$ is a matrix and $\mathbf{b}_m$ is a vector, representing the coefficients and constants of the parametric constraints, respectively. Each row of $\mathbf{A}_m$, paired with the corresponding element in $\mathbf{b}_m$, defines a half-space. The polytope H_m is the intersection of all these half-spaces.

The I-dimensional polytope H can be defined by all the polytopes H_m, denoted $\bigcup_m H_m = H$. The polytope H represents all feasible combinations of zonal total loads $\mathbf{D}^P$.

As shown in (18), the m-th polytope of $\mathbf{D}^P$ is typically defined by a set of linear inequalities. Given this polytope and a set of linear transformations (19), the net positions $\mathbf{F}_m$ can be calculated and expressed as piecewise affine functions of the zonal total loads $\mathbf{D}^P$.

$$\begin{aligned} \mathbf{F}_m &= \mathbf{G}_m^* - \mathbf{D}^P + \mathbf{E}_m^* \\ &= (\mathbf{u}_m^G - \mathbf{I} + \mathbf{u}_m^E)\mathbf{D}^P + \mathbf{v}_m^G + \mathbf{v}_m^E \end{aligned} \tag{19}$$

where **I** is the $I\times I$ unit matrix.

C. Parameter Space and ENS Conditions

The parametric solution represents the parameter space in Monte Carlo simulations using the I-dimensional polytope H, which describes the zonal total loads across a total of I zones. Through the piecewise affine functions (19) for net positions, we can calculate the net positions based on the zonal total loads $\mathbf{D}^P$ and validate the FB domains according to constraints (1). Importantly, an additional verification step becomes unnecessary since these specific constraints have been incorporated within constraints (15).

The parameter space of polytope H has a flexible nature, allowing for seamless adjustments to accommodate varying ENS conditions. This adaptability is achieved by altering the values of $E_i^{\max}$ within constraints (12). The different values of $E_i^{\max}$ lead to a corresponding expansion or contraction of the polytope H. Consequently, the parameter space in Monte Carlo simulations undergoes corresponding modifications. A specific ENS condition occurs when the values of $E_i^{\max}$ are all zeros. This results in the polytope H taking its smallest size under no ENS conditions.

Upon establishing a specific ENS condition, we can compute the associated polytope H of zonal total loads. Following this calculation, the parameter space in Monte Carlo simulations is defined based on polytope H, and then a large number of samples within this specific region are generated. Utilizing the piecewise affine function (17), we can directly map the ENS values for these samples. Through an analysis of these samples, the probability of ENS occurrence is calculated. Subsequent STA assessments can then perform a more detailed analysis based on these scenarios for a thorough examination. Therefore, the proposed method supports the alignment with each Monte Carlo scenario generated for the probabilistic adequacy assessments.

IV. Case Studies

There are five zones in the CWE electric power system in the European market. In this paper, a 5-area system is constructed to validate the proposed method, with external factors modified from the European market data [12][21]. The polytope of zonal total loads across all five zones represents the parameter space in Monte Carlo simulations.

A. Test System

To provide an illustration of the proposed method, a 5-area system is utilized as shown in Fig. 1.

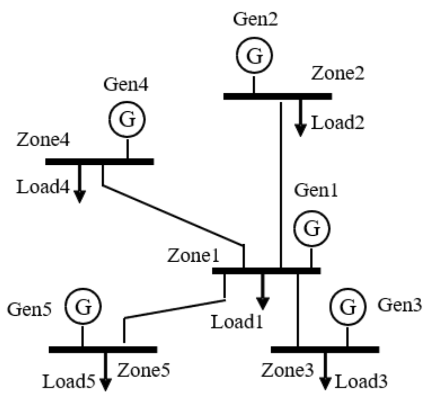


Fig. 1. 5-area system.

The necessary information for each zone, including the availability of generation capacities, the expected total loads and operational security limits, is known for all five areas. Each zone only considers aggregated generator variables, an aggregated total load, and the RAM, which is also pre-defined by the 'base case,' as executed in [5].

The values of $E_i^{\max}$ in all areas are defined as a proportion α of the expected total loads. Consider the instance where α is set to 0, which defines a parameter space in Monte Carlo simulations represented by the smallest polytope H of zonal total loads. In this case, polytope H operates under no ENS conditions. When α is set to 0.1, it permits an ENS of up to 10% of the expected total loads for each zone during the sampling process. This paper compares the outcomes and implications of parameter spaces when α is set to 0, 0.1, and

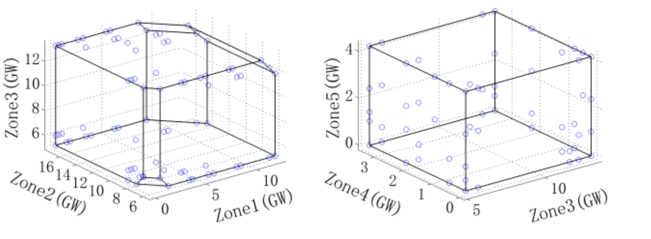
0.3, providing a comprehensive analysis of the impact of different ENS conditions.

It is crucial to highlight that since we have modeled the zonal total loads as programming parameters in model (9)-(16), the expected total loads do not directly determine the net positions and decision variables. Instead, they play a subtle yet integral role as they are implicitly factored into the constraints (12) and (14).

B. Parameter Space under Didfferent ENS Conditons

To facilitate a clear comparison, we visualize the five-dimensional (5D) polytope of zonal total loads within a three-dimensional (3D) space. When we set α to 0, we identify the polytope of zonal total loads through 179 distinct vertices, collectively defining this 5D polytope. As illustrated in Fig. 2, we employ blue points to denote the vertices and black lines to exhibit the polytope's projection across two 3D spaces. Here, each blue point within the 3D space correlates to a corresponding vertex in the 5D polytope, with every axis representing the feasible range of zonal total load for its corresponding zone.

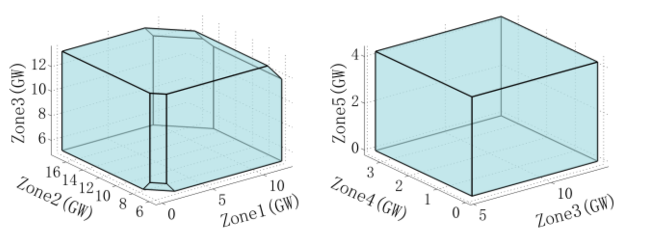
These vertices originate from the implementation of model (9)-(16), incorporating constraints from the FB domains. As a result, the 5D polytope for zonal total loads is more restricted compared to the polytope defined by the FB domains alone.



(a) (b)

Fig. 2. Vertices of a 5D polytope projected onto a 3D space at α=0 (a) Vertices projected onto (Zone1, Zone2, Zone3) space (b) Vertices projected onto (Zone3, Zone4, Zone5) space.

Maintaining α at 0, the parameter space in Monte Carlo simulations without ENS coincides with the 5D polytope of zonal total loads. Fig. 3 illustrates the 5D polytope projected onto two 3D spaces, ensuring all points within the 5D polytope are feasible, thus achieving full coverage. When this polytope is used as the parameter space in Monte Carlo simulations, it guarantees the elimination of ENS scenarios. If the Monte Carlo simulation samples combinations of loads in the polytope of zonal total loads, the generated scenarios automatically satisfy the pre-defined FB domain.

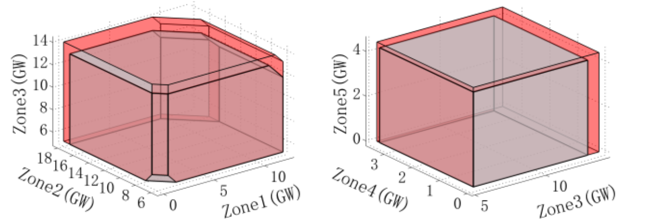


(a) (b)

Fig. 3. Parameter space under no ENS conditions at α=0 (a) Polytope projected in (Zone1, Zone2, Zone3) space (b) Polytope projected in (Zone3, Zone4, Zone5) space.

Subsequently, we explore how the parameter space adapts under varying ENS conditions, setting α to 0.1 for this analysis. Fig. 4 illustrates the expansion of the parameter space in Monte Carlo simulations as α increases from 0 to 0.1, showcasing the parameter spaces for α=0 and α=0.1 with blue and red polytopes, respectively. Both Fig. 4(a) and Fig. 4(b) provide two 3D perspectives to better visualize and comprehend this expansion.

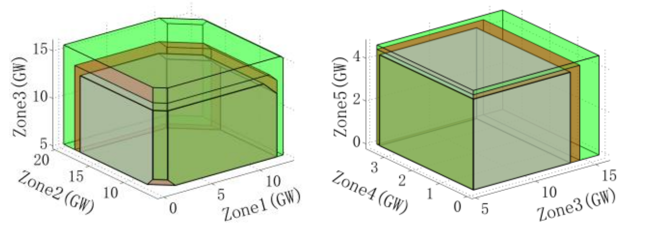
When α is set to 0.1, accommodating for ENS conditions, the parameter space expands, reflecting an increase in feasible range of zonal total load for the corresponding zone. Utilizing the α=0.1 polytope as the parameter space in Monte Carlo simulations facilitates the estimation of the ENS occurrence probability, ensuring it remains below 0.1. In this setting, numerous Monte Carlo samples are generated. Samples within the blue polyhedron do not result in ENS, while those located inside the red but outside the blue polyhedron do. This comprehensive sampling approach enables an accurate determination of ENS probabilities under the specified conditions of α=0.1.



(a) (b)

Fig. 4. Expansion of parameter space at α=0.1 (a) Polytope projected in (Zone1, Zone2, Zone3) space (b) Polytope projected in (Zone3, Zone4, Zone5) space.

When α is increased to 0.3, the parameter space experiences a significant enlargement, as illustrated by the green polytope in Fig. 5. Both Fig. 5(a) and Fig. 5(b) provide 3D views to observe this expansion. Similarly, a substantial number of Monte Carlo samples are generated. Samples within the blue polyhedron indicate scenarios without ENS, while those within the green polytope but outside the blue polyhedron result in ENS. This extensive sampling allows for an accurate estimation of ENS under the given conditions (α=0.3). More importantly, this setting also enables the estimation of ENS probability between the red and green polytopes, facilitating more precise risk assessments for specific scenarios. This quantification of ENS risk between different parameter spaces underscores the method's value. It enhances our understanding of system behavior under varying conditions and better prepares stakeholders to mitigate potential risks.



(a) (b)

Fig. 5. Expansion of parameter space at α=0.3 (a) Polytope projected in (Zone1, Zone2, Zone3) space (b) Polytope projected in (Zone3, Zone4, Zone5) space.

Analyzing the results in Fig. 3, Fig. 4, and Fig. 5, it becomes apparent that ENS affects different zones disproportionately. Some zones exhibit substantial changes in the range of zonal total loads, whereas others maintain relative stability. This variation primarily stems from differences in external factors, including the availability of generation capacities and the capacities of cross-border tie lines.

Taking zone 1 as an example, it has ample cross-border tie line capacities. In scenarios where ENS impacts other zones but does not appear in zone 1, this zone has the capability to import additional electricity from the affected zones via the cross-border tie lines. This capability effectively broadens the feasible range of zonal total load for zone 1, as evidenced by Fig. 5(a). Other zones can also use ENS to increase the range of zonal total load for a specific zone, provided that the cross-border tie lines are sufficient. As a result, the polytope expands in response to increasing ENS conditions.

The range of zonal total load for zone 4 is less affected than that for zone 1, mainly due to its limited cross-border tie line capacities. The theoretical maximum zonal total load for any given zone depends on its tie line capacities as well as the availability of generation capacities. Once tie line capacities are maximized, the zonal total load becomes reliant on availability of generation capacities. It is important to note that the maximum generation capacities remain constant, unless there are changes in external factors. As shown in Fig. 5(b), zone 4's electricity import approaches its limit of tie line capacities. In situations where ENS conditions impact other zones, zone 4 can potentially augment its electricity imports up to the tie line capacities. Beyond this capacity limit, the zonal total load range for zone 4 remains stable, unless additional tie line or generation capacities are introduced.

In conclusion, the parametric programming model establishes a parameter space in Monte Carlo simulations, guaranteeing a precise and consistent alignment with each Monte Carlo scenario generated for probabilistic adequacy assessments. This model distinctly provides the polytope in the parameter space where ENS does not occur, enhancing the clarity of the STA assessments. Furthermore, it enables us to accurately estimate the ranges within which specific ENS values are likely to occur, adding another layer of precision to STA analyses.

V. Conclusions

Short-Term Adequacy (STA) assessments are pivotal for identifying risks and ensuring the European electric power system's reliability and security. This paper introduces a parametric programming model that integrates with Flow-Based (FB) domains to identify available zonal total loads efficiently. The model derives a polytope of zonal total loads, considering a correlation between external factors and the polytope of net positions within FB domains. Additionally, this model tackles the prevalent issue of Energy Not Served (ENS) and ensures corresponding polytopes across various ENS conditions. These polytopes guarantee consistent alignment with each Monte Carlo scenario generated for probabilistic adequacy assessments. Serving as a refined parameter space in Monte Carlo simulations, each polytope sets the stage for enhanced accuracy in subsequent STA assessments. The case studies validate that the proposed method can offer not only a parameter space in Monte Carlo simulations exempt from ENS issues, but also provide results corresponding to specific ENS conditions.

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