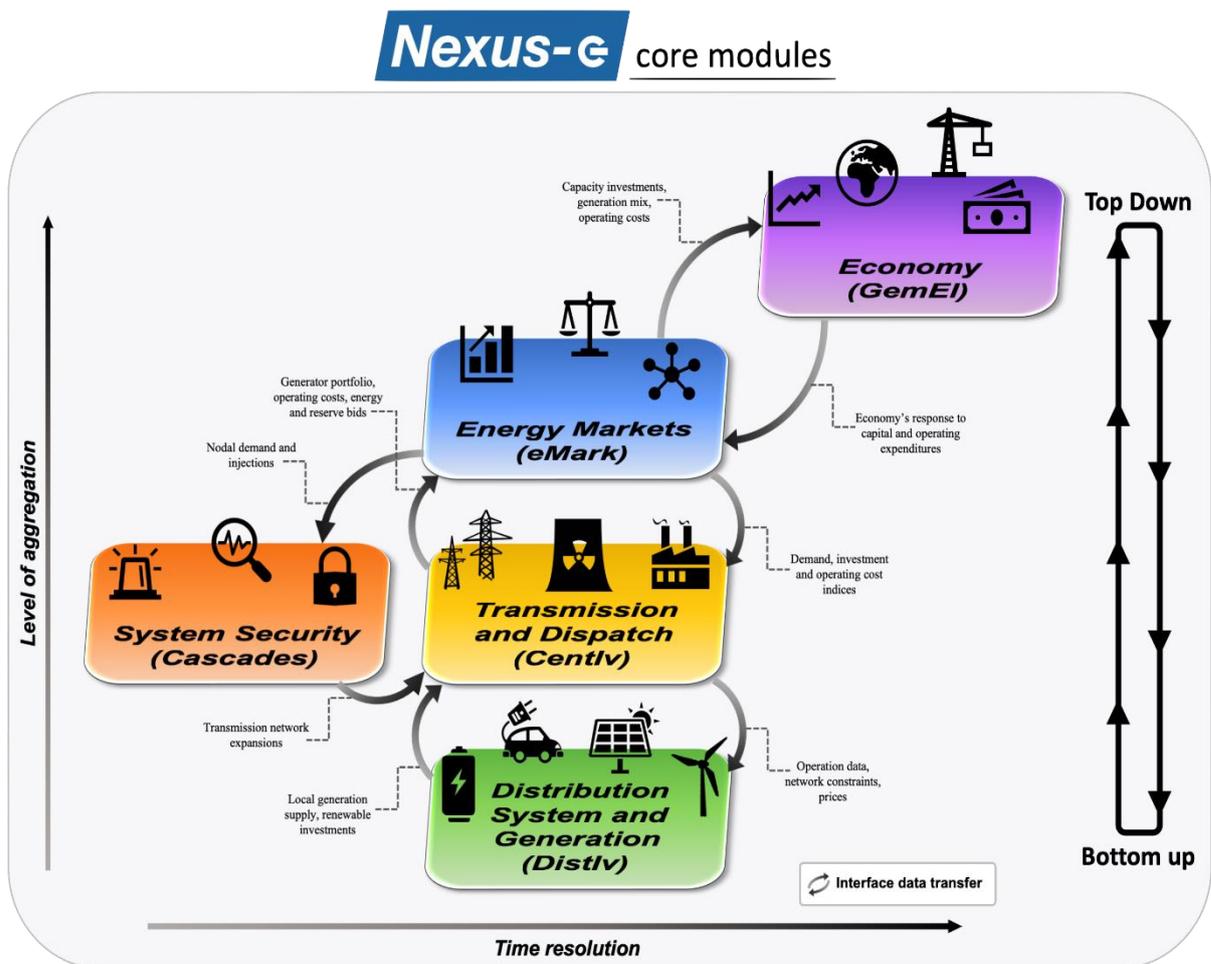




Final report

Nexus-e: Integrated Energy Systems Modeling Platform

Cascades Module Documentation





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Summary

Policy changes in the energy sector result in wide-ranging implications throughout the entire energy system and influence all sectors of the economy. Due partly to the high complexity of combining separate models, few attempts have been undertaken to model the interactions between the components of the energy-economic system. The Nexus-e Integrated Energy Systems Modeling Platform aims to fill this gap by providing an interdisciplinary framework of modules that are linked through well-defined interfaces to holistically analyze and understand the impacts of future developments in the energy system. This platform combines bottom-up and top-down energy modeling approaches to represent a much broader scope of the energy-economic system than traditional stand-alone modeling approaches.

In Phase 1 of this project, the objective is to develop a novel tool for the analysis of the Swiss electricity system. This study illustrates the capabilities of Nexus-e in answering the crucial questions of how centralized and distributed flexibility technologies could be deployed in the Swiss electricity system and how they would impact the traditional operation of the system. The aim of the analysis is not policy advice, as some critical developments like the European net-zero emissions goal are not yet included in the scenarios, but rather to illustrate the unique capabilities of the Nexus-e modeling framework. To answer these questions, consistent technical representations of a wide spectrum of current and novel energy supply, demand, and storage technologies are needed as well as a thorough economic evaluation of different investment incentives and the impact investments have on the wider economy. Moreover, these aspects need to be combined with modeling of the long- and short-term electricity market structures and electricity networks. This report illustrates the capabilities of the Nexus-e platform.

The Nexus-e Platform consists of five interlinked modules:

- General Equilibrium Module for Electricity (GemEI): a computable general equilibrium (CGE) module of the Swiss economy,
- Centralized Investments Module (Centlv): a grid-constrained generation expansion planning (GEP) module considering system flexibility requirements,
- Distributed Investments Module (Distlv): a GEP module of distributed energy resources,
- Electricity Market Module (eMark): a market-based dispatch module for determining generator production schedules and electricity market prices,
- Network Security and Expansion Module (Cascades): a power system security assessment and transmission system expansion planning module.

This report provides the description and documentation for the Cascades module, which is utilized in the Nexus-e framework to assess the security of supply by testing the capability of a power system to withstand sudden changes, and to provide a transmission system expansion plan if a target level of security is not satisfied.



Zusammenfassung

Politische Veränderungen im Energiesektor haben weitreichende Auswirkungen auf das gesamte Energiesystem und beeinflussen alle Sektoren der Wirtschaft. Aufgrund der hohen Komplexität der Energiewirtschaft, wurden bisher nur wenige Versuche unternommen, die Wechselwirkungen zwischen den einzelnen Komponenten dieses Systems zu modellieren. Nexus-e, eine Plattform für die Modellierung von integrierten Energiesystemen, schliesst diese Lücke und schafft eine interdisziplinäre Plattform, in welcher verschiedene Module über klar definierten Schnittstellen miteinander verbunden sind. Dadurch können die Auswirkungen zukünftiger Entwicklungen in der Energiewirtschaft ganzheitlich analysiert und verstanden werden. Die Nexus-e Plattform ermöglicht die Kombination von „Bottom-Up“ und „Top-Down“ Energiemodellen und ermöglicht es dadurch, einen breiteren Bereich der Energiewirtschaft abzubilden als dies bei traditionellen Modellierungsansätzen der Fall ist.

Phase 1 dieses Projekts zielt darauf ab, ein neuartiges Instrument für die Analyse des schweizerischen Elektrizitätssystems zu entwickeln. Um die Möglichkeiten von Nexus-e zu veranschaulichen, untersuchen wir die Frage, wie zentrale und dezentrale Flexibilitätstechnologien im schweizerischen Elektrizitätssystem eingesetzt werden können und wie sie sich auf den traditionellen Betrieb des Energiesystems auswirken würden. Ziel der Analyse ist es nicht Empfehlungen für die Politik zu geben, da einige wichtige Entwicklungen wie das Europäische Netto-Null-Emissionsziel noch nicht in den Szenarien enthalten sind. Vielmehr möchten wir die einzigartigen Fähigkeiten der Modellierungsplattform Nexus-e vorstellen. Um diese Fragen zu beantworten, ist eine konsistente technische Darstellungen aktueller und neuartiger Energieversorgungs-, Nachfrage- und Speichertechnologien, sowie eine gründliche wirtschaftliche Bewertung der verschiedenen Investitionsanreize und der Auswirkungen der Investitionen auf die Gesamtwirtschaft erforderlich. Darüber hinaus müssen diese Aspekte mit der Modellierung der lang- und kurzfristigen Strommarktstrukturen und Stromnetze kombiniert werden. Dieser Report veranschaulicht die Fähigkeiten der Nexus-e Plattform.

Die Nexus-e Plattform besteht aus fünf miteinander verknüpften Modulen:

- Allgemeines Gleichgewichtsmodul für Elektrizität (GemEI): ein Modul zur Darstellung des allgemeinen Gleichgewichts (CGE) der Schweizer Wirtschaft,
- Investitionsmodul für zentrale Energiesysteme (Centlv): ein Modul zur Planung des netzgebundenen Erzeugungsausbaus (GEP) unter Berücksichtigung der Anforderungen an die Systemflexibilität,
- Investitionsmodul für dezentrale Energiesysteme (Distlv): ein GEP-Modul für dezentrale Energieerzeugung,
- Strommarktmodul (eMark): ein marktorientiertes Dispatch-Modul zur Bestimmung von Generator-Produktionsplänen und Strommarktpreisen,
- Netzsicherheits- und Erweiterungsmodul (Cascades): ein Modul zur Bewertung der Sicherheit des Energiesystems und zur Planung der Erweiterung des Übertragungsnetzes.

Dieser Bericht beinhaltet die Beschreibung und Dokumentation des Cascades-Moduls. Dieses Model wird im Rahmen von Nexus-e verwendet, um die Versorgungssicherheit zu bewerten, indem die Fähigkeit eines Stromversorgungssystems getestet wird plötzlichen Veränderungen zu widerstehen, und um einen Plan für den Ausbau des Übertragungssystems zu erstellen, falls ein angestrebtes Sicherheitsniveau nicht erreicht wird.



Résumé

Les changements de politique dans le secteur de l'énergie ont de vastes répercussions sur l'ensemble du système énergétique et influencent tous les secteurs de l'économie. En partie à cause de la grande complexité de la combinaison de modèles séparés, peu de tentatives ont été entreprises pour modéliser les interactions entre les composantes du système économique-énergétique. La plateforme de modélisation des systèmes énergétiques intégrés Nexus-e vise à combler cette lacune en fournissant un cadre interdisciplinaire de modules qui sont reliés par des interfaces bien définies pour analyser et comprendre de manière holistique l'impact des développements futurs du système énergétique. Cette plateforme combine des approches de modélisation énergétique ascendante et descendante pour représenter un champ d'application beaucoup plus large du système économique-énergétique que les approches de modélisation indépendantes traditionnelles.

Dans la phase 1 de ce projet, l'objectif est de développer un nouvel outil pour l'analyse du système électrique suisse. Cette étude sert à illustrer les capacités de Nexus-e à répondre aux questions cruciales de comment les technologies de flexibilité centralisées et décentralisées pourraient être déployées dans le système électrique suisse et comment elles affecteraient le fonctionnement traditionnel du système. Le but de cette analyse n'est pas d'offrir de conseils politiques, en tant que les scénarios ne considèrent pas des développements critiques comme l'objectif Européen d'atteindre zéro émission nette, mais d'illustrer les capacités uniques de la plateforme Nexus. Pour répondre à ces questions, des représentations techniques cohérentes d'un large éventail de technologies actuelles et nouvelles d'approvisionnement, de demande et de stockage d'énergie sont nécessaires, ainsi qu'une évaluation économique approfondie des différentes incitations à l'investissement et de l'impact des investissements sur l'économie au sens large. En outre, ces aspects doivent être combinés avec la modélisation des structures du marché de l'électricité et des réseaux d'électricité à long et à court terme. Ce rapport illustre les capacités de la plateforme Nexus-e.

La plateforme Nexus-e se compose de cinq modules interconnectés:

- Module d'équilibre général pour l'électricité (GemEI): un module d'équilibre général calculable (EGC) de l'économie suisse,
- Module d'investissements centralisés (Centlv): un module de planification de l'expansion de la production (PEP) soumise aux contraintes du réseau, qui tient compte des exigences de flexibilité du système,
- Module d'investissements distribués (Distlv): un module PEP de la production décentralisée d'énergie,
- Module du marché de l'électricité (eMark): un module de répartition basé sur le marché pour déterminer les calendriers de production des producteurs et les prix du marché de l'électricité,
- Module de sécurité et d'expansion du réseau (Cascades): un module d'évaluation de la sécurité du système électrique et de planification de l'expansion du système de transmission.

Ce rapport fournit la description et la documentation du module Cascades, qui est utilisé dans le cadre de Nexus-e pour évaluer la sécurité de l'approvisionnement en testant la capacité d'un réseau électrique à résister à des changements soudains, et pour fournir un plan d'expansion du réseau de transmission si un niveau de sécurité cible n'est pas atteint.



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Abbreviations

CCDF	complementary cumulative distribution function
DNS	demand not served
FCR	frequency containment reserve
FD	fast decoupled
FRR	frequency restoration reserve
GS	Gauss-Seidel
IEEE	Institute of Electrical and Electronics Engineers
NR	Newton-Raphson
OPF	optimal power flow
PF	power flow
UFLS	under-frequency load shedding
UVLS	under-voltage load shedding
WECC	Western Electricity Coordinating Council

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1 Introduction

1.1 Module purpose

The purpose of the Cascades module is to: (1) assess the security of supply by testing the capability of a power system to withstand sudden changes, i.e. due to component failures; and (2) to provide a transmission system expansion plan if a target level of security is not satisfied. The Cascades module comprises two models, a cascading failure simulations model and a transmission system expansion planning model.

1.2 Process overview

The security of supply is assessed with a cascading failure simulations model. The model is initialized with sets of contingencies, i.e. potential critical failures that may trigger cascading events. After an initial failure is introduced, the model identifies island operations and blackout conditions in the power system. Furthermore, the model simulates system automation by performing automatic frequency control to restore the power balance in the system by deployment of generation reserves. Moreover, the model simulates automatic load shedding in case of system frequency deviations beyond a safety threshold or bus voltage magnitudes below a tolerable limit. To calculate the power flows and bus voltages the model utilizes an AC power flow algorithm. In addition, the model disconnects transmission elements (lines and transformers) due to overloads, i.e. violation of the branch power ratings.

The transmission expansion planning is performed using a transmission system expansion planning model. The model relies on two importance lists, which rank the branches from most important to least important with respect to different criteria. Based on the rankings, expansion upgrades are proposed, and then each upgrade is assessed using the cascading failure simulation model. The branch upgrade providing the best security improvement is added to an expansion list. The process is iteratively repeated until a predefined level of security is satisfied or an expansion budget is reached.

1.3 Attributes

The following list characterizes some of the main module attributes:

- Deterministic, steady-state model for power system security analysis
- Applies probabilistically selected sets of contingencies (Monte-Carlo approach)
- Evaluates different load and generator conditions at selected time intervals (hours)
- It simulates power system automated responses that react in short time scales (seconds, minutes)
- Needs detailed grid and generation unit data
- Uses various solvers for Power Flow and Optimal Power Flow.

1.4 Capabilities

The following list describes some of the main capabilities of this module:

- Performs AC and DC cascading failure analyses
- Performs expansion planning using different criteria
 - Target security
 - Available budget
 - Maximum expansions / upgrades



1.5 Limitations

The following list provides context on some of the main limitations of Cascades:

- The stochastic behavior of the power systems is limited to the initial contingencies
- Transients, e.g. generator swing equations, are neglected
- Voltage control is not considered (under-voltage emergency protection is implemented)
- The expansion planning uses only the existing branches as candidates

1.6 Inputs and outputs

Table 1 and Table 2 list the Cascades module's required input data and resulting output data, respectively. It is important to note that the module receives the input data (Table 1) through the eMark-Cascades interface. However, in a stand-alone run Cascades pulls the data from a dedicated MySQL database. In this case, the module calculates the generator dispatch and uses the remaining available capacity as generating reserves. Cascades uses additional input data such as the line failure probability of branches (lines and transformers), and the under-frequency load shedding (UFLS) and under-voltage load shedding (UVLS) steps, which are encoded in the algorithm, and described later in this report.

Table 1: List of input data.

Variable	Resolution	Unit	Description
Generator data	by unit	various	Location, capacity, costs, operational parameters, etc.
Grid topology	-	various	Detailed transmission network data (buses, branches, transformers)
Demand	hourly, nodal	MW	Nodal hourly transmission system demand
Generator dispatch	hourly, nodal	MW	Generator power injections in each hour
Reserves	hourly, nodal	MW	Generator power injections in each hour

Table 2: List of output data.

Variable	Resolution	Unit	Description
Branch data	-	various	Expansion plan, i.e. branches to be upgraded
DNS	-	-	A complementary cumulative distribution function, i.e. risk curve
Outage occurrence	-	-	Transmission system component outage occurrence
Cascading stages	-	MW	the lines/transformers tripped at each stage and the corresponding DNS
Importance	-	-	Importance/criticality of the transmission system components
Reserves utilization	-	MW	The what extend each unit is used to provide reserves



2 Related work and contributions

Recent wide-area blackouts such as the 2011 Southwest blackout in Arizona and South California [1] and the record-breaking blackout in India [2], suggest that concerns regarding blackout threats in transmission systems are well grounded. In response to that, a growing number of analytical and simulation methods are emerging for studying the cascading failure in order to prevent and mitigate blackouts and improve the reliability of power grids [3]. Herein we provide a review of the most widely applied research-grade cascading failure analysis tools [4].

Hidden Failure (HF) Model

The HF is a AC PF based model with primary focus on modeling of hidden failures thermal overload and generator re-dispatch [5]. The hidden failures of the protection system are modeled by probabilistic approaches. Fast simulation technique and heuristic random search are applied to identify the critical relays that contribute significantly to the cascades. Maintaining these relays can mitigate cascading failures effectively. However, this approach relies heavily on the availability of protection data.

OPA Model

OPA model [6] studies the complex dynamics of an upgrading power system with cascading line outages. The cascading events are triggered by random line outages, and the line overloads are evaluated with DC load flow. The overloaded lines are triggered with a fixed probability. After a line outage, the generation and load are re-dispatched using standard linear programming methods with the objective of minimizing the load shedding. The distinctive feature of the OPA is that the dynamics of the power system upgrade is accounted.

Manchester

In the Manchester model [7], a range of cascading failure interactions is presented, which includes the cascading tripping of lines, generator instability, under frequency load shedding, post-contingency re-dispatch and emergency load shedding for preventing voltage collapse. The model runs an AC PF and requires the failure probability of generation and transmission components as well as the probabilities of hidden failures as the inputs. The probability of failures can be adjusted according to the effect of weather conditions and the model estimates the time required to restore the load following an outage.

Section 3 of this document presents the details of the Cascades module which encompasses an AC based cascading failure simulation model that is similar in concept to the Manchester model.



3 Detailed description of the Cascades module

Cascades is a system security analysis module comprising: (1) a cascading failure simulations model and (2) a power system expansion planning model. In the following, both models are described in detail.

3.1 Cascading failure simulations model

The cascading failure model provides insights into the adequacy of the capacity of a transmission system. The model is characterized by the following functions:

- Simulation of critical scenarios that may trigger a cascading event,
- Identification of island operation within the system,
- Deployment of generation reserves to restore the power balance in the system in case of a generation/consumption mismatch or island formation
- Triggering of load shedding due to system frequency deviations beyond a safety threshold/ bus voltages magnitudes falling below a tolerable limit
- Identification of blackout conditions in island operation resulting from large power imbalances that cause frequency instability
- Computation of the load flow changes across the transmission grid using power flow methods
- Disconnection of overloaded power lines/transformers.

3.1.1 Modeling features

The cascading failure analysis model procedure is described in the following 12 steps (see Figure 1):

1. *Initial system state*

The initial system state is the starting point of the model. All of the components in the system are in service and loads are equal to the forecast. There are no overloads, and the units generate power according to a given optimal power flow. In case the dispatch is provided by another module/algorithm and results in overloads, Cascades continues the simulations considering these overloads, as well.

2. *N-k contingencies*

Here, single or multiple line and transformer contingencies are introduced to initiate sudden (unexpected) changes in the transmission system and investigate how the resilience of the system is affected by these changes. By default we use a random failure mechanism to initiate failures of lines/transformers based on their failure probability. The procedure starts by creating a vector of uniformly generated random numbers between 0 and 1. The size of the vector is equal to the number of lines and transformers in the system, such that each element in the vector corresponds to a particular component. If an element in the generated vector has a value equal or smaller than the failure probability of the corresponding component, this component is considered failed and added to a contingency list. This procedure is repeated until the contingency list has reached a predefined size.

We use a single probability value for all elements in the system. Due to the low failure probability of power system components only a single contingency is found in most runs; double or even triple contingencies are sampled only very infrequently. In the end, the contingency list consists of a predefined number of sets of contingencies, where each set contains single or multiple line or transformer outages.

The selection of contingencies is executed via Monte-Carlo sampling. Therefore, the larger the contingency list the higher the chance of exploring different sets of contingencies and, thus, obtaining a more comprehensive evaluation of the system risk. For each set on the contingency list a cascading failure simulation is run. After selecting a single set, the related component(s) are removed from the system and a new system topology is obtained.



3. Island identification

The new topology of the system is checked to see if any islands were created because of the contingency. If this is the case, the buses belonging to the respective islands are identified.

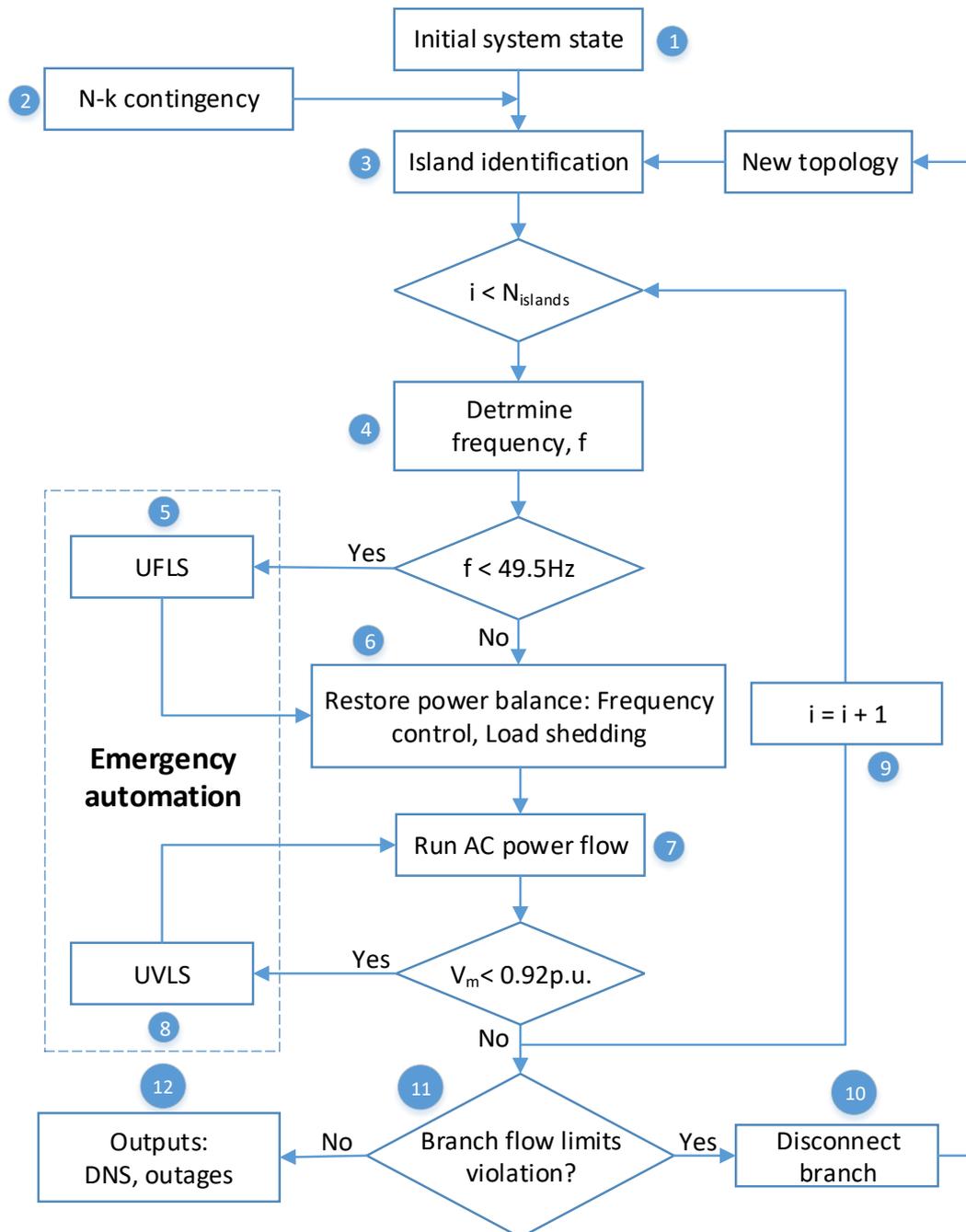


Figure 1: The cascading failure simulation algorithm flow-chart.

4. Check frequency deviation

The frequency deviation is computed using the following equation [8]:



$$\Delta f = \frac{-\Delta P_{\text{imbalance}}}{\sum_{\Omega_G} 1/R_g} \quad (1)$$

where $\Delta P_{\text{imbalance}}$ is the active power imbalance in MW, Ω_G represents the set of generators, and R_g is the frequency characteristic of g th generator (speed droop) in Hz/MW.

5. *Emergency automation – frequency*

Emergency under-frequency load shedding (UFLS) schemes are the last measure to be taken in order to maintain power system stability after a major disturbance. In principle, whenever the frequency deviation is in the allowed range but the available capacities of the synchronized generating units are unable to satisfy the load, the UFLS automation uniformly disconnects just enough load to reach a new power balance and to avoid a large-scale collapse of the system [8].

The UFLS scheme used in Cascades is based on the Swissgrid transmission code 2013 [9]. It consists of six steps: if the frequency is smaller than 49.5 Hz, the pumped-storage hydro plant operating in pumping regime are disconnected; following are four steps of uniformly disconnecting load proportional to the frequency deviation; finally, if the frequency drops for 2.5 Hz or increases for 1.5 Hz of the nominal, all generators are disconnected.

6. *Restore load-generation balance*

As the equation (1) shows, the frequency deviation in the system is proportional to the power imbalance. If there is a variation of load demand or island operation in the system, the balance between the power generation and load consumption in the system/island may not be maintained. The imbalance is measured as the difference between the change of load and the change of generation [10, 11]:

$$\Delta P_{\text{imbalance}} = \Delta P_l - \Delta P_g \quad (2)$$

Restoring the load-generation-balance and, thus, the frequency in the system is performed by frequency control actions. When a frequency deviation occurs, all the generators connected to the system or the island will ramp up/down to increase/decrease their power output in order to compensate for the power imbalance. Generators change the power delivery proportional to their ramp rates and are limited by their maximum/minimum operating limits. For the extreme case, that there is no load connected to an island, all the generators are shut down. In general, generating units reach their new operating points typically in tens of seconds for primary frequency control, and in a few minutes for secondary frequency control [12].

7. *Power flow calculations*

After restoring the load-generation balance, a power flow study (AC or DC) is performed. In case of AC power flow a voltage stability check is performed and the cascading failure simulations continue with step 8. In case of DC power flow the cascading failure simulation continues directly with step 9, i.e. with an overload check of the transmission system branches.

8. *Emergency automation – voltage*

A system may enter a state of voltage instability when it is subject to a disturbance. The steady-state threshold is a post-contingency voltage of 92% of the nominal voltage, or 0.92 p.u. [13]. One of the most economical remedial actions to voltage drop is under-voltage load shedding (UVLS) [14]. In order to implement UVLS, the location and magnitude of a voltage drop must be identified. In Cascades, under-voltage load shedding is applied to the load directly connected to the bus where the voltage violation occurs. In the first step, 25% of the initial load is shed, and the voltage magnitude is updated by the AC power flow algorithm. If the voltage violation persists, this procedure is repeated until the voltage magnitude is restored back to ≥ 0.92 p.u. If under-voltage load shedding cannot restore the voltage, the entire load connected to the bus is lost.



9. *Island evaluation*

Steps 4 to 8 are applied to all islands, updating the power flows and bus characteristics of each island.

10. *Branch flow limit violation*

After the power flows in each island have been updated, branches with power flows higher than their tripping threshold/maximum transmission capacity are identified. Only one line at a time is tripped, i.e. the line with the highest overload. The new system topology is returned to Step 3 for island identification.

11. *Termination criteria*

The simulation is terminated when there are no branch flow violations.

12. *Output results*

Besides the demand not served (DNS) and number of lines/transformers tripped for each set of contingencies, the model records the impact of each line/transformer on the DNS, the frequency of line/transformer overload, the cascading stages and the corresponding DNS at each stage, and the utilization of each unit in positive and negative reserves.

The procedure from 1 to 12 is repeated for different loading conditions, sampled from a yearly load curve. The cascading failure results obtained for each loading condition, are assembled, processed, and presented as an output from the model. One of the most important results of the cascading failure model is the complementary cumulative distribution function (CCDF) of the DNS. We will refer to it as the cascading failure risk curve, or simply risk curve. The risk curve gives the probability of observing DNS (blackout intensity) at least as extreme than the one observed.

3.1.2 Algorithm features

Cascades incorporates two cascading failure analysis models: the first one relies on DC power flow, while the second is AC power flow-based. The preferred choice for solving the AC power flow problem is the Newton-Raphson (NR) method; however, the Gauss-Seidel (GS) and Fast Decoupled (FDXB and FDBX) methods are also available. The main difference between the two models is that the DC-based model does not evaluate bus voltages and, therefore, UVLS cannot be performed. Furthermore, the AC model calculates the reactive power flows in the grid, which is not the case with the DC model. Consequently, it can be expected that the AC-based model will yield more load shedding events and requires more computing time. Both models use MATPOWER package [15] for solving the optimal power flow (OPF) and the power flow (PF) problems that are part of the simulations. Furthermore, an additional DC-based cascading failure model is available for testing purposes. This model is different from the default DC model because it relies on in-built function for the DC power flow calculation and MATLAB's "lineprog.m" for the OPF.

The cascading failure model can utilize any of the two available methods for automatic frequency control: (1) the default method; and (2) the procured reserves based method. When the default method is applied, every available unit is ramped up or down based on the current generation level, and their ramp rates as described in Section 3.1.6. The procured reserves based method only uses the reserves schedule provided by a market/dispatch model. Here the primary and secondary reserves are combined and treated as one; this applies to both the positive and the negative reserves. The tertiary reserves are activated in case the primary and secondary reserves are not sufficient to balance the load demand. In both methods generators are ramped up according to their individual ramp up rates. For the negative reserves, besides using the ramp down rates, an additional option is offered where the ramp down is performed proportional to the current output of the units. For both frequency control methods, the model records the utilization of the reserves from each unit, both positive and negative. These results can later



be used to perform better reserves procurement from a security perspective, i.e. to provide higher flexibility in the parts of the system where it is mostly needed.

AC power flow convergence is not always guaranteed and there is a possibility that the algorithm will fail to obtain solutions under certain conditions. There are various reasons for non-convergence, from an inadequate initial guess of the bus voltages to voltage collapse. Before any measures are taken we run simulations using the four available AC PF methods, i.e. NR, FDXB, FDBX, and the GS PF method. Each of these methods have different convergence properties, thus, the one showing the fewest convergence issues is selected. When a cascading failure investigation is carried out, it is likely that for some system configurations the AC power flow will not converge due to the system operating outside the steady state stability limits. This can be the result of a reduced capacity of the system to transfer the power from one part to another, or a lack of reactive power to supply load demand, causing a voltage collapse in some parts of the system. We run a continuation PF to check for system stability limit violations. To mitigate the convergence problem, a built-in mechanism that can resolve convergence issues is implemented. The mechanism can take action in four different ways and, depending on the order in which they are applied, four strategies exist. These actions are: (1) decrease system loading, i.e. decrease the load and generation simultaneously step-by-step until the AC PF converges; (2) perform full AC OPF; (3) accept the non-converged solution or consider system blackout; (4) perform reactive power AC OPF, i.e. fix the active power and run the AC OPF, which results in reactive power re-dispatch. The preferred (default) order is (1)-(2)-(3), and if (1) is not successful (2) is used and so forth. Current tests show that in the majority of non-convergence cases action (1) is sufficient; action (3) is only used in extremely rare situations. When action (3) is used, we accept the non-converged solution (the default option) and simulate how the cascade progresses. Current tests show that if none of the above actions is leading to convergence, the non-converged solution is likely to have large active/reactive power flows in some parts of the system, resulting in overloads. This means that if this solution is accepted, it is very likely that the cascading will progress further, causing blackouts. However, the option exists that when action (3) is used a total system collapse is acknowledged, i.e. the algorithm sheds all load and disconnects all generation. The default value of the load/generator reduction in action (1) is 5%. Smaller values are not recommended as it may result in longer calculation times, while higher values may result in unnecessary load shedding.

In case where the minimum and maximum operational constraints of the slack bus are violated in the AC PF solution a correction is performed. Namely, the power output is reduced to the maximum allowed value if the maximum power limit constraint is violated, or increased to the minimum allowed value if the minimum power limit is violated. The power difference is covered by the reserves or, alternatively, load shedding is performed. AC power flow studies can result in unrealistic reactive power flows that, in turn, cause unrealistic power losses. This issue is resolved by ignoring the losses and treating the power flow as DC. It is worth mentioning that these events are very rare and occur in some systems more often than in others. The algorithm also has the option to cancel this step.

The AC-based cascading failure model is adapted to receive generation schedules from a DC-based dispatch (obtained by a unit commitment / generation scheduling algorithm). The difference between the AC-based dispatch and the DC-based dispatch is in the power losses occurring in the transmission lines, which are neglected in the DC approximation. Thus, when a DC dispatch is fed into an AC model, there will be a power loss mismatch that must be compensated by the slack bus, which may not be the most economical solution or may even be unfeasible, as the compensation would violate the maximum power limit constraint of the slack bus. Therefore, a procedure is created that performs a re-dispatch enabling losses to be distributed to the cheapest generators with available capacity. In the process, all generators keep the value provided by the DC dispatch except the ones that have to increase their power output to compensate for the losses. The generators will increase the power output based on the available capacity such that, if they are scheduled to provide reserves, the reserves are not depleted.



However, in case the total amount of additionally available generator power is smaller than the losses, the algorithm will use some of the scheduled reserves.

If the data consists of multiple zones (interconnected power systems, operated independently), the algorithm will treat them as one, sharing all available reserves among zones. Future work will upgrade the algorithm to perform independent automatic actions within each zone, like secondary frequency control and emergency load shedding actions. However, if the neighboring zones of the analyzed zone are aggregated, the algorithm offers two options: (1) if there is export reduction into a neighboring zone due to events occurring in the zone of interest, add this amount in to the total DNS; (2) only account for the events occurring in the analyzed zone, ignoring potential DNS due to export reduction in the neighboring zones.

We use only one failure probability for all lines and transformers in the system, with a default value of 0.001. Furthermore, there is the option to use single line rating coefficients (line tripping thresholds) for all the lines or multiple ratings for different classes of lines. The purpose of those coefficients is for use as tuning parameters when model calibration is performed. When a single line rating coefficient is used a single value is set for all lines and transformers in the system. When multiple line rating coefficients are used, a unique value is assigned to each component based on the voltage level, i.e. the number of coefficients is equal to the number of unique voltage levels. A value of 1, corresponding to the nominal line ratings is assigned as the default. The line failure probability and line rating coefficients are decision variables in a validation and model calibration procedure we have developed [16]. The procedure is based on meta-heuristics with the objective of finding the optimal values for the line failure probability and rating, which will enable the simulation results to have the best possible agreement with historical data. We have performed this type of model calibration for the Western Electricity Coordinating Council (WECC) network, for which historical data on DNS and line outages is available [17, 18].

3.2 Transmission system expansion planning model

The objective of the transmission system expansion planning model is to provide an expansion plan that achieves a predefined system security. This system security can either be the amount of DNS according to historical data or the amount of DNS resulting from simulations of a reference system configuration. The selection of the type of system security depends on the availability of historical data for the analyzed power system. Herein, the predefined system security will be referred to as the reference security data. Furthermore, if a budget for power system expansion is given, the model maximizes the security within the given budget. Note that the current model only proposes upgrades of existing branches (parallel line or transformer).

3.2.1 Modeling features

The transmission system expansion planning model relies on the cascading failure analysis model to derive expansion strategies. Two concepts are used: (1) the first concept is based on the impact of line/transformer failures on the DNS, which relies on the cascading failure model recording all events where an initial contingency results in load shedding. (2) The second concept is based on the frequency of line overloads; this concept relies on the cascading failure model recording all line overloads occurring after an initial contingency. The model performs the following steps (Figure 2):

1. *Creation of lists*

The impact of line/transformer failures on the DNS, as well as the frequency of line overloads are stored in two lists, after which the transmission system lines/transformers are ranked from highest to lowest frequency/impact. Additionally, a third list is created as a hybrid of both lists. The hybrid list must not have repeating lines/transformers, i.e. if a line/transformer exists in both list the one with the highest rank is kept in the hybrid list.

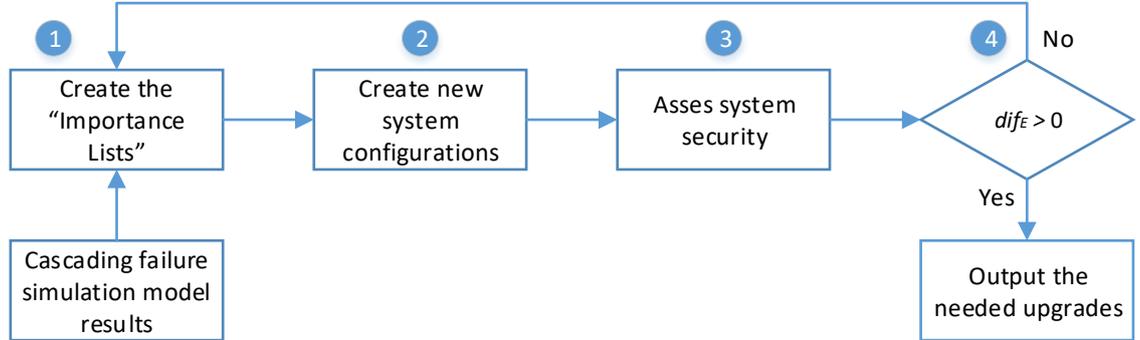


Figure 2: Expansion planning model flow chart.

2. Expansion strategy

Each list is used to create an expansion strategy, and each strategy is used to create a new/updated network topology. Therefore, three new network configurations are formed. The number of lines/transformers to be upgraded from each list is predefined, with the recommended number of line/transformer upgrades being equal to one, i.e. only one line/transformer should be upgraded in each iteration. This procedure prevents over-investments in the system; however, upgrading only one component per iteration can also lead to long computing times.

3. Asses the expansion impact

After each network configuration has been evaluated separately using the cascading failure simulation algorithm, the obtained results are compared. This comparison is based on the difference between the simulation results and the (desired) reference system security. One of the main results from the cascading failure model is the distribution of DNS events. Consequently, we calculate the difference between the simulated and the reference DNS distributions. The algorithm has several options for calculating this difference, such as distance correlation [19], Kolmogorov-Smirnov test [20, 21], Kullback-Leibler divergence [22], and Minkowski distance [23]. The latter is computed as follows:

$$dif_E = \left(\sum |CCDF_{DNS_{DATA}}(dns_{DATA}) - CCDF_{DNS}(dns)|^p \right)^{1/p} \quad (4)$$

where dif_E is a measure of the differences between reference data and simulation results, $CCDF_{DNS_{DATA}}$ is the complementary cumulative distribution function (CCDF) of the historical DNS, $CCDF_{DNS}$ is the CCDF of the simulation results, dns_{DATA} and dns are the DNS value vectors, $p = 1$ results in the Manhattan distance, while $p = 2$ yields the Euclidean distance. Because the reference data and the simulation data may not contain the same number of DNS values, both vectors are interpolated using linear polynomials to construct new data points within a discrete range, thus making the subtraction possible. Equation (4) always results in a positive number for both $p = 1$ and $p = 2$. It is, therefore, crucial to know the sign of the function difference, which in this case is determined only as the sum of the differences between the CCDF of the reference data and the CCDF of the simulation results. A negative sign means that the security obtained with the simulations is lower than the security of the system for which the reference data is given.

The function difference (distance) is calculated for all three new system configurations and only the system resulting in the highest function difference is kept, the others are discarded. In case the required system security is not yet reached, the results obtained from the cascading failure simulations of the other two system configurations are used to create the new importance lists, which will be further evaluated.



4. *Stopping criteria*

The function difference is also used as a stopping criteria. In other words the expansion planning continues until the function difference becomes a positive value or a predefined number of iterations is reached.

3.2.2 Algorithm features

The default setting of the transmission system expansion planning algorithm is to calculate and use the function difference based on the DNS results. However, the line outage probability function difference can be used as an alternative. This difference is calculated as the difference between the line outage data (historical or reference system configuration) and the simulation results. One must not confuse the failure probability of a line with the line outage probability. The latter is calculated based on the participation of each type of outage in the total number of outages. In other words, the number of all single component outages is divided by the total number of outages, the number of all double component outages is divided by the total number of outages etc.

Besides the system security, an expansion budget can also be used as the main criterion for the expansion plan, enabling the algorithm to find the best expansion plan considering a given budget. Violation of the budget is possible. If neither a security criterion nor budget exists, the user is motivated to use a maximum number of upgrades.

The expansion planning algorithm can be executed significantly faster if the user chooses to use only one expansion strategy and, thus, only one new system configuration is evaluated at a time. Once the expansion method has been applied on a given power system, it becomes evident which expansion strategy is giving the best result. Therefore, for further utilization of the algorithm on the same system, the user is encouraged to use the strategy that is clearly giving the best results without calculating the security impact of the other two strategies. However, if the system is significantly changed the user should reassess the expansion strategies and re-select the most adequate one. In case the calculation time is not a concern, it is recommended that the user selects the default option, i.e. assessing and comparing all strategies.

3.3 Cascades simulations options

Besides the possibility of choosing between different cascading failure simulation models and different expansion strategies Cascades can be utilized in two modes: (1) stand-alone mode, in which the module runs on its own and executes the analyses based on already existing data, and (2) interfaced mode, in which Cascades is part of the Nexus-e platform where it exchanges data/results with other modules.

Furthermore, the user can select the number of demand hours from a yearly demand curve and the number of simulations per demand hour. Cascades has the option to select random hours from the load demand curve as well as different representative demand hours, e.g. number of peak loads from each season, and a combination of peak loads and random hours for each season. As explained in the N-K contingencies section, the number of contingencies is randomly selected based on the component failure probability. However, the algorithm also has the option to save contingency lists and reload them every time Cascades is executed. This option is valuable when one needs to compare the results from different cascading failure simulations of the same system and cannot afford to use a large number of simulations/contingencies. The number of contingencies and demand hours needed to thoroughly explore the system risk depends on the system size. For systems of the order of the 24-bus IEEE test system the number of contingencies should be higher than 1000, and the number of demand hours at least 18.



Cascades can be executed in parallel, based either on the contingencies or on the number of simulation hours. Therefore, the user is encouraged to select one of the parallel execution options, which will result in smaller computational times. If this option is selected, the algorithm distributes the work automatically to the available CPU cores or to the number of preselected cores (this setting is available in the MATLAB parallelization toolbox).



4 Flexibility

The flexibility by Cascades module is captured through the utilization of available generating reserves. In other words, the system frequency changes when the initial failures (contingencies) and the subsequent cascading outages result in loss of generator or loss of load in the system. When the frequency deviation is within the limits and thus UFLS is not required, the load-generation-balance is restored by frequency control, i.e. the power reserves. Therefore, the amount of available and dispatchable (flexible) units and their location in the grid will affect system stability and determine if all load will be supplied. In case that insufficient generation flexibility exists, the frequency restoration is performed by load shedding. In this case, the algorithm records the amount of load shedding as DNS, which is represented with the risk curve. Overall, the lack of flexibility in the power system will have a negative effect on the security of supply and thus will contribute to the risk of systemic failures, which is captured by the Cascades module. Note that the system security is influenced by multiple factors, including the generation mix, the share of dispatchable units in the mix, their ramp rates, the location of the units in the grid, the transmission capacity, the demand, and the imports/export.



5 Description of interfaces

The Cascades module is interconnected with the eMark model, i.e. two interfaces are established: 1) the eMark-Cascades interface, and 2) the Cascades-eMark interface. Through the eMark-Cascades interface, eMark provides Cascades with the power output of each unit (generation dispatch), the power exchange between Switzerland and the neighboring countries (imports and exports), and the procured power reserves (frequency containment reserve (FCR), positive and negative frequency restoration reserve (FRR)) that each generating unit in the power system provides (see Table 3). The time resolution of the provided data is one hour and the time horizon is one year. Additionally, eMark passes the power system physical, the final list of power generation capacities to the Cascades module, and the final hourly power demand. Note that the reserves procurement provided by eMark are not used in the current analyses. Instead, all available generators are utilized in providing load-generator balance considering the generator's operating limits (ramp rates and minimum/maximum output thresholds) as described in Section 3.1.6.

Table 3: eMark-Cascades module interface details.

Variable	Resolution	Unit	Description
mpc version	-	-	Version for MatPower mpc structure
mpc base MVA	-	MVA	Base MVA assumed for MatPower mpc
mpc bus data	by bus	various	Bus data in MatPower format
mpc branch data	by branch	various	Line data in MatPower format
mpc gen data	by unit	various	Generator data in MatPower format
mpc gen cost data	by unit	various	Generator cost data in MatPower format
mpc gen info data	by unit	various	Additional generator information
Load realization	hourly, nodal	MW	Nodal power demand in each hour
Generation positions	hourly, nodal	MW	Generator power injections in each hour
FCR procurements	hourly, nodal	MW	Generator power injections in each hour
Positive FRR procurements	hourly, nodal	MW	Generator power injections in each hour
Negative FRR procurements	hourly, nodal	MW	Generator power injections in each hour
Flow type	-	-	The power flow type (AC, DC)
Swiss zone number	-	-	The Swiss zone number

The list of branches to be built/upgraded is updated at each iteration between Cascades and eMark, and the full list is transferred to eMark. In other words, eMark is receiving a list of branches that consists of the branches from the current iteration and all previous iterations (Table 4). The exchange of information between the modules continues until Cascades shows no need for further upgrades in the transmission system, i.e. after the reference security is reached. Furthermore, if there is no significant improvements to the security over the iterations, although new branches are proposed, the loop is stopped after a predefined iteration number is reached.

Table 4: Cascades-eMark module interface details.

Variable	Resolution	Unit	Description
mpc branch data (new)	-	-	branches to be upgraded in MatPower format



6 Demonstration of results

To exemplify the utilization of the Cascades module, we perform analyses of the modified IEEE 24-bus test power system¹. The demonstration results in this section serve as an example of how the Cascades model can be used to assess system security and provide transmission system expansion planning. These results are only for illustrative purposes and are not meant to represent the final results of the Nexus-e simulation framework for any particular scenario.

The blue curve in Figure 3 (a) shows the risk curve, i.e. complementary cumulative distribution function (CCDF) of demands not served (DNS), i.e. blackouts obtained by the cascading failure simulation model using multiple simulations for multiple contingencies and multiple representable load demands selected from a yearly load curve. Let us assume that this is a representation of the system security we are satisfied with, and we want to keep the same level in the future as well. In the next step, we assume that the system has changed. For demonstration purposes, one line and one transformer were removed. The obtained results (the red distribution in Figure 3 (a)) show that the system security has been reduced (the risk of systemic failures has increased). The goal is to improve the system security, i.e. to bring it as close as possible to the previous (desired) level. Therefore, we apply the transmission system expansion planning model. The model aims at maximizing the function difference between both distributions. In the particular case, the function difference is -25 (determined as the Euclidian distance between the distributions (see Section 3.1.2)). The obtained results after the proposed system upgrades are represented by the red distribution in Figure 3 (b). The system security is almost identical to the desired level, with a function difference equal to 0.8.

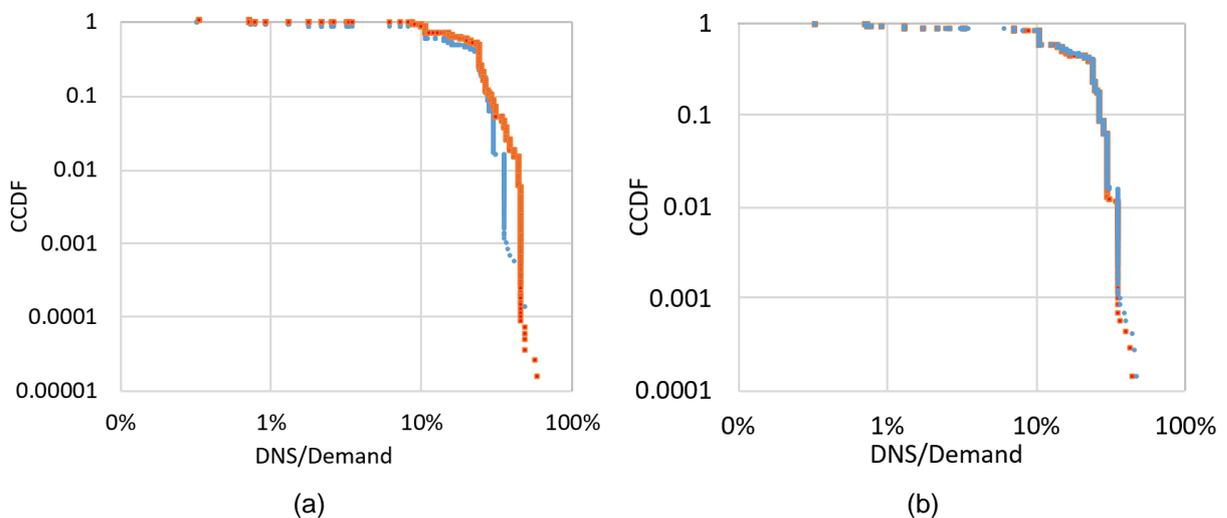


Figure 3: An example results of the Cascades module: the risk curve (CCDF of DNS) of the analyzed system (a) before and after performed changes, and (b) after system upgrades in comparison of the initial (target) system security.

¹ This system is used only for demonstrative purposes and does not resemble the Swiss power system.



7 Publications

A list of publications related to the Cascades Module (chronological order):

- An article [17] presented at ESREL 2019 conference provides a comparison of different simulation based optimization techniques and function difference methods for calibration of cascading failure simulation models. As calibration parameters, we use a unique branch rating multiplier for all branches with the same voltage level.
- An article [16] presented at the PMAPS 2018 describes a multi-objective and multi-parameter method for validation and calibration of DC based cascading failure simulation models. As calibration parameter we use a single branch failure probability and single branch rating parameter. As objective functions we use the function difference between the historical DNS and simulated DNS, and the function difference between the historical number of branch failures and simulate number of branch failures.
- An article [10] published at IEEE system journal presents a framework that uniquely integrates an ac power flow based cascading failure analysis for the electric network with a multiregional, multi-industry interdependence model to quantify the short-term economic impacts of electric power disruption due to cascading failures.
- An article [18] presented at the 2017 IEEE Power & Energy Society General Meeting describes a single objective optimization method based calibration of cascading failure models. The method utilizes a Genetic Algorithm to find the optimal probability of branch failure so the simulated DNS distribution is in the best agreement with the historical DNS data.
- An article [11] presented at the 2016 IEEE Power and Energy Society General Meeting shows a cascading failure simulation model, which captures power system operations, protections, automatic regulations, and remedial action schemes. The model relies on linear implicit AC power flow, which provides a tradeoff between computationally expensive AC power flow and approximate DC power flow.



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