A Vision to Enhance Transmission Security

The Case of Switzerland's Power System

IT IS HARD TO IMAGINE LIFE WITHOUT ELECTRICITY. Electrical energy is constantly consumed to allow humanity to carry out diverse activities ranging from charging mobile phones to controlling the flow of vehicles and pedestrians with traffic lights. Due to its widespread usage and significance, some people take the availability of electric power for granted and expect that the lights will always turn on when they turn on the switch. Nevertheless, when illuminating our rooms, we need to appreciate that an extensive power system infrastructure is in place to securely generate, transport, and distribute electrical energy to our homes.

Electric power systems have been undergoing massive changes over the last few decades. This includes the integration of high levels of small-scale energy resources in distribution grids, the electrification of transportation and heating/cooling sectors, higher volatility due to uncertain power in-feed from renewable energy generation, the internationalization of energy markets, and increasing public opposition to grid expansion, just to name a few. These changes make it increasingly challenging to maintain the security of supply in the power system.

Power system security is defined as the ability of the system to withstand sudden disturbances or unanticipated loss

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of system elements and is closely related to system adequacy, reliability, and integrity. This article is concerned with security issues in the operation of the high-voltage transmission grid originating from environmental or transmission constraints and focuses on the case of Switzerland. Specifically, we focus on steady-state insecurity, namely violations in transmission line flows or bus voltage limits following a component contingency, without considering dynamic aspects such as maintaining synchronism and system stability following the disturbance.

First, we describe today's operational philosophy of Swissgrid, the Swiss transmission system operator (TSO), which is also commonly applied by other European TSOs. Next, we identify potential risks of this operational philosophy, which we exemplify through discussion of recent grid events in the Swiss power system and link to observed trends in system operation. Finally, we argue that a new operational paradigm is needed to mitigate such risks in the transmission grid of the future. This new philosophy relies on data analytics and decision support systems (DSSs) to assist the work of system operators, and we provide examples of recent relevant initiatives at Swissgrid.

Security Challenges and Today's Transmission System Operator Operational Philosophy

Power system security is one of the key responsibilities of TSOs. This article elaborates on how system security is addressed in the planning and operational procedures in Switzerland. Despite the Swiss focus, the principles of the operational philosophy outlined here apply to several other European TSOs as well.

The Unique Characteristics of the Swiss Power System

The Swiss transmission system is very strongly interconnected with its neighboring countries. There are, in fact, 41 cross-border transmission lines compared to about 160 lines that both start and end within Switzerland.

The Swiss transmission system evolved organically by following the residential and commercial activity patterns as well as the natural energy sources. Thus, the consumption centers are located in the north, together with run-of-river hydropower plants and nuclear stations, whereas the storage and pumped-storage plants (in other words, the more flexible power plants) are in the Alps in the south. The strongest transmission path runs from the north to the south, or rather southeast, from where it extends to Italy. Historical flows naturally followed the structure of the transmission lines, with the cross-border exchange joining in dominantly with the imports from France and Germany and exports toward Italy.

The Swiss power system features another characteristic that is not common in most other continental European systems: the subtransmission system and some distribution systems do not have a radial structure but are rather strongly meshed and connected to transmission nodes in several locations. Thus, they accommodate part of the power flows in parallel to the transmission lines.

The installed production capacity exceeds 20 GW, with the peak consumption being approximately 11.5 GW, so the traditional adequacy assessment does not reveal the weakness of the system, which is the energy scarcity in particular months due to the seasonality in water inflows. This is caused by the utilization of water in the reservoirs of hydropower plants during winter, which only start to refill again in the summer when snow in the Alps melts.

Switzerland has adopted a self-scheduling market design, with the vast majority of transactions taking place "over-the-counter" on a typically bilateral basis between the market participants. Only a small portion of transactions are "visible" in the power exchange. There is no explicit connection between transactions and the underlying physical assets. All technical constraints of the power plants are embedded into the transactions or bids. Although electricity transactions have to respect the net transfer capacities among countries, the transmission constraints on the level of individual transmission lines are not explicitly included in the market activities—the assumption of a "copper plate" is applied. If congestion in network elements occurs as a result of the market activities, it is the responsibility of the TSO to apply remedial actions to mitigate them.

From an organizational point of view, the Swiss electricity landscape is quite fragmented for a system with an annual consumption of about 65 TWh. There are about 80 power plant companies, even though they often have similar shareholders, and more than 600 distribution system operators (DSOs). About 100 balance responsible parties group consumers and producers for scheduling and electricity transit purposes. Switzerland is surrounded by member countries of the European Union subjected to its legislation, which is not directly adopted by Switzerland.

Operation and Operational Planning

The factors described in the previous section imply that the operation of the Swiss transmission system is strongly affected by annual seasonality, short-term volatility, the availability of timely and accurate information/data from other stakeholders, and limited enforceability or intervention possibilities. These challenges are addressed in a set of procedures spanning various geographical ranges and time scales.

- ✔ *Day-ahead regional (cross-border) coordinated operational planning*: To capture the effect of various parts of the interconnected system on other parts, TSOs of continental Europe exchange their data for the coming day and carry out a coordinated security assessment. If they recognize a risk, which can be mitigated only by an action in another country, they place the corresponding request. First, topological measures (e.g., reconfiguring busbars in a substation) are checked, and if the computed effect is not sufficient, a preventive redispatch (or, more precisely expressed, countertrading) is triggered among TSOs. Alternatively, transmission capacities between the countries are restricted for the trading activities of the following day.
- ✔ *Day-ahead operational planning in Switzerland*: The data from the stakeholders are collected first, including expected power plant schedules, consumption forecasts, and planned cross-border exchanges. An N–1 security assessment in the form of contingency screening is applied for the expected deterministic scenario. In the case of congestions in the production regions, congestion warnings are issued to the producers. Some topological measures may be applied. No redispatch actions take place as further trading activities may take place in the intraday market.
- ✔ *Intraday and real-time operation*: Switzerland is not included in the electricity market coupling of the European Union member states. Thus, the Swiss system is occasionally subjected to a sudden change of the transmission flows with minimal previous awareness. Also, stakeholders within Switzerland may change their positions and actions communicated in the day-ahead market on very short notice due to a variety of reasons. Therefore, a rolling security assessment forecast is carried out every 15 min for the period of the subsequent 4 h. Operators may then decide which countermeasures to employ and in which sequence (preventive, corrective) to guarantee security. Again, typically topological measures are applied first, when available, which are mostly determined by operators based on experience or simulation-based methodologies. If no suitable topological measure is available, redispatch is employed within Switzerland or if no national redispatch measure is available, cross-border redispatch with the neighboring TSOs is applied.

The Maintenance of Transmission Assets

The maintenance of transmission assets naturally takes place in the summer months as environmental conditions are most favorable at that time, especially in the Alps, and the

> In general, a comprehensive medium-term energy security planning process is needed, which includes planned grid and power plant outages, hydro storage levels, and market conditions.

electricity demand is lowest in summer, not necessitating the availability of all power plants.

The process follows a bottom-up approach: transmission assets are grouped according to region, with the regional manager submitting the maintenance requests for approval. The requests are checked by the operational planning team in order of submission, applying rough assumptions about the expected system conditions as the future system state is not accurately known or forecasted. This means there is also little information about the assumed availability of possible corrective actions.

Power plants similarly announce their maintenance schedules on an individual basis. Their unavailability is considered for the system security assessment, but the TSO has only an advisory role in rescheduling, with the only exception being the power plants contracted for black start and islanding operation capability.

Note that data exchange with DSOs takes place only to a limited extent in the planning stage. Thus, when maintenance takes place in the distribution grid, the transmission system may be affected in real time without the detailed awareness on the side of the TSO.

Historical Grid Events in the Swiss System

Although today's operational philosophy has been largely successful in maintaining the security of the power supply, some recent grid events have demonstrated growing potential risks due to the evolution of the changes to which the system is subjected. This section discusses several recent events and attempts to identify relevant aspects of the operational philosophy that could be improved to better handle such situations in the future.

The Winter 2015–2016 Situation

A problematic supply and grid situation was identified in December 2015 due to a combination of circumstances. Dry weather conditions during summer and autumn led to lower power generation from run-of-river plants. The filling levels of hydro storage plants published by the Swiss Office of Energy were below the long-term annual average. Moreover, nuclear power reactors Beznau 1 and 2 on the 220-kV level were out of operation, totaling 720 MW of missing power in-feed.

The missing base production from run-of-river and nuclear plants had to be compensated by imports and production from hydro storage plants. While the supply of Swiss consumers is mostly via the 220-kV level, up to 85% of imported power comes in via the 380-kV level during wintertime. Since the transformation capacity between the 380- and 220-kV level was limited, the risk of premature depletion of the hydro storage dams (most of them are connected to the 220-kV network) followed by a lack of energy supply increased. The problem was amplified due to the rather high energy prices at the beginning of the winter, which resulted in many Swiss hydro storage power plants often exporting energy. An illustration of the problem related to the limited production resources in the 220-kV network is given in Figure 1.

To mitigate these problems, a temporary connection of the transformer in Laufenburg that allowed transformation between the 380- and 220-kV networks was carried out, and a reserve transformer was commissioned in Tierfehd, as depicted in Figure 2. Moreover, topological measures in Werben and Bürs increased the import on the 220-kV level from Austria via the Rhine valley. The outcome of these measures was to increase the net transfer capacity to France, Germany, and Austria during peak times. To allow for a higher import to cover the domestic consumption in Switzerland, monthly export products (cross-border capacity) to neighboring countries were made unavailable during winter. The measures taken by Swissgrid, together with the unusually mild, rainy winter weather and the recommissioning of block 2 of the Beznau nuclear power plant on 23 and 24 December 2015, helped improve the grid situation from the Christmas holidays 2015–2016 onwards.

This event demonstrated the challenges in maintaining the overall adequacy and security of supply in an electricity system with unbundled production and grid operation. Swissgrid is responsible for maintaining network security, but no entity in Switzerland is in charge of ensuring the overall security of supply. In general, a comprehensive medium-term energy security planning process is needed, which includes planned grid and power plant outages, hydro storage levels, and market conditions.

Grid Security Violation on 20 May 2019

Due to attractive market conditions, there was an unusually high generation of electrical power in Switzerland (up to 12 GW) on 20 May 2019 as well as a high net export to neighboring countries (up to 4.5 GW). In particular, there was high planned export to Germany (up to 4 GW export, whereas Switzerland typically imports from Germany), very low export to Italy (1.3 GW, which is quite uncommon), and import from France (600 MW). This export situation to the north, unusual in comparison to the past, is potentially problematic for the Swiss transmission grid and might result in congestion because production has to be transported to the north via the 220-kV grid within Switzerland.

On top of this unusual export pattern, the concurrence of several other factors led to a security violation. In the distribution grid, several outages planned by a DSO were executed, and these were not known to the TSO. In the same region of the distribution grid, transit flows from the transmission grid through the distribution grid caused the overloading of a distribution line and the need for an unplanned outage of the affected line, of which the TSO was not aware. These topological changes in the distribution grid due to the execution of planned outages and actions to avoid overloading the line, which were unexpected for the TSO, required topological measures (transformer phase shifts) in the transmission grid. These, in turn, led to load redistribution. Furthermore, there were short-term production increases planned and communicated only shortly before real time. The combination of these factors led to overloading a 220-kV network element and multiple N–1 violations on the 220-kV level of the transmission grid.

The following aspects were identified as the main causes of this event:

- ✔ the uncommon export situation and high energy production in Switzerland together with short-term changes in power production schedules
- ✔ the effect of topological changes in the distribution grid on the transmission grid as well as the effect of topological measures in the transmission grid on the load allocation in the lower-voltage grids.

Whereas the first point is mostly related to the expansion planning of the Swiss power grid, the second one is related to today's operational philosophy. Specifically, the congestion forecast tool was unable to predict the violations of transmission grid elements in time because the subtransmission and distribution networks are not included in the model. Therefore, the main lesson from this grid event is the importance of having an operational philosophy that considers the subtransmission and distribution networks (or at least important networked parts of them) both in outage planning and real-time operations.

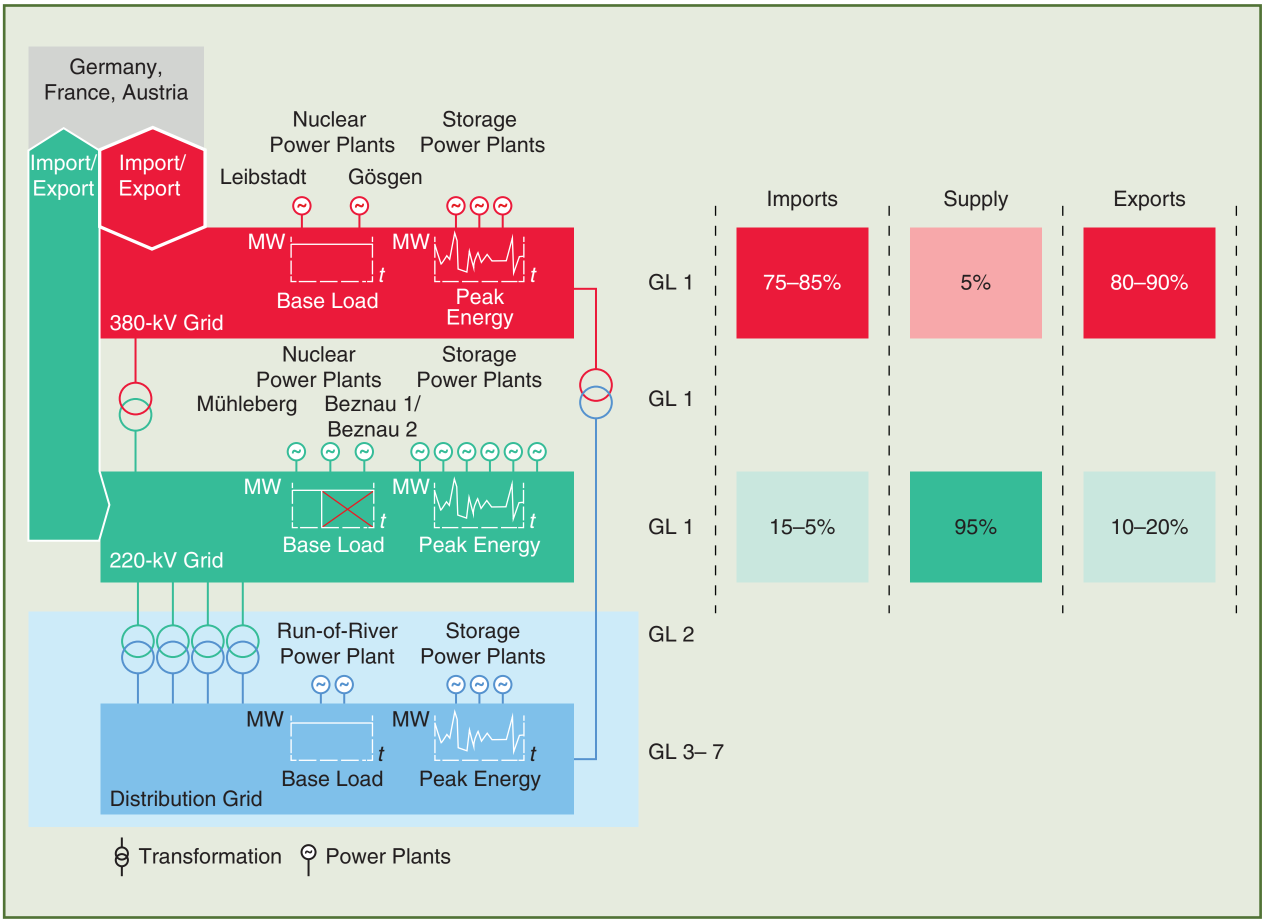

figure 1. An illustration of the cause of the winter 2015–2016 situation with most of the load, but only limited power production and import, in the 220-kV grid. Import was mainly via the 380-kV level, but the transformation capacity between the 380- and 220-kV levels was limited.

Minimum Production Product in Winter 2019–2020

Following the plan for phasing out nuclear power in Switzerland, the Mühleberg nuclear power plant was decommissioned in November 2019. The decommissioning coincided with limited controllability and capacity limitations for the Bassecourt transformer and delays in the commissioning of a new transformer in Mühleberg. As a consequence, and assuming that the missing power was to be compensated by additional import from the north, i.e., by increasing the net transfer capacity to Austria, Germany, and France, some network elements in Western Switzerland (especially the transformer in Bassecourt) were expected to be overloaded during the low consumption period between Christmas 2019 and New Year 2020.

To guarantee grid security in the region between Bassecourt, Mühleberg, and Chamoson, Swissgrid agreed upon a minimum level of production with selected power plants in Western Switzerland from 20 December 2019 to 6 January 2020. Specifically, the selected power plants agreed to cumulatively produce a minimum of 200 MW at off-peak times and 400 MW at peak times. This longer-term preventive measure was shown to be preferable and more economical to alternative measures, such as reducing the net transfer capacity to Austria, Germany, and France (i.e., to incentivize Swiss power plants to increase production) or resorting to many shorter-term national and/or international redispatch calls closer to real-time operation.

This is a relevant example of real-world situations where new measures against grid insecurity must be devised by system operators in a short amount of time. Despite the measure's success, this event demonstrated the value of an integrated approach for outage planning and the selection of remedial actions, which can include the design of new or customized products such as longer-term minimum power production products. TSOs would benefit from a new operational paradigm, including such an integrated planning and operation approach.

COVID-19 Lockdown in March–April 2020

As a measure against the spread of COVID-19, the Swiss Federal Council ordered the closing of stores and public venues starting 16 March 2020. Neighboring European countries took similar measures around the same point in time.

As a consequence, the domestic energy consumption during weekdays and the energy flows in and across the Swiss

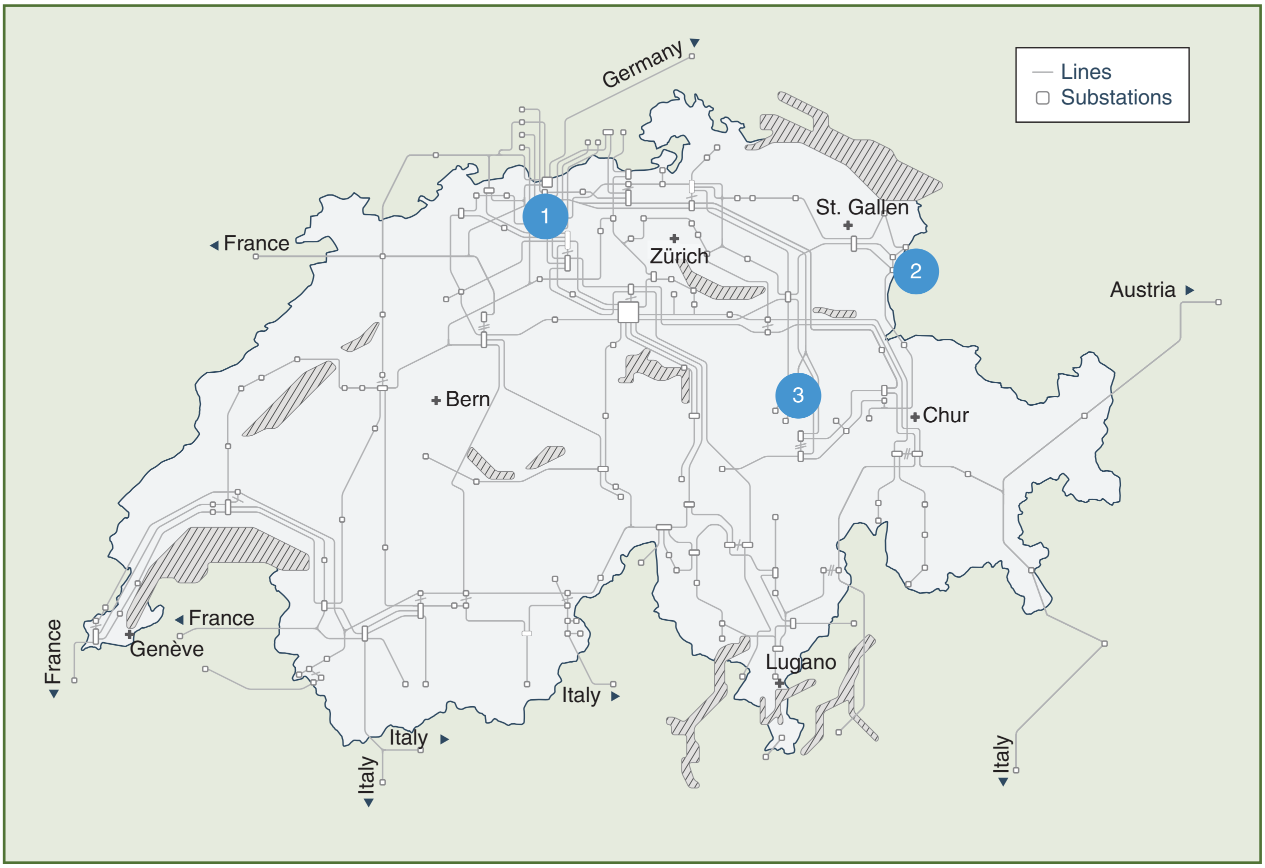

figure 2. The measures applied to relieve the stressed grid situation in winter 2015–2016. Location 1: a temporary connection of the transformer in Laufenburg to allow for transformation between the 380- and 220-kV networks. Location 2: the topological measures to increase the import on the 220-kV level from Austria via the Rhine Valley. Location 3: the commissioning of a reserve transformer in Tierfehd.

network decreased significantly. Figure 3 illustrates the country-wise aggregated load profile right before and after the lockdown, where the sudden reduction in consumption is apparent. The subsequent higher injection of reactive power from distribution grids (because feeder cables are capacitive at light loading conditions) and the lower inductive absorption of reactive power in transmission lines increased the risk of local overvoltages. To mitigate this risk, additional reactive power reserves were activated. Also, topological measures (e.g., line switching and transformer tapping) were implemented to decrease or redistribute reactive power flows.

As mentioned in the "Operation and Operational Planning" section, preventive remedial actions are typically determined by the operators based on experience or computed using simulation-based approaches. Due to the advantages of optimization-based methods, such methods are being investigated by some TSOs for determining the best remedial actions. Optimization models are mostly based on dc network models as they target avoiding line overloadings. Nevertheless, the COVID-19 situation showed the significance of an operational philosophy allowing system operators to implement preventive measures to circumvent voltage violations in addition to typical curative measures. To efficiently and systematically compute preventive measures against voltage violations, optimization models that can handle ac network models would be required together with the associated computational and algorithmic innovations.

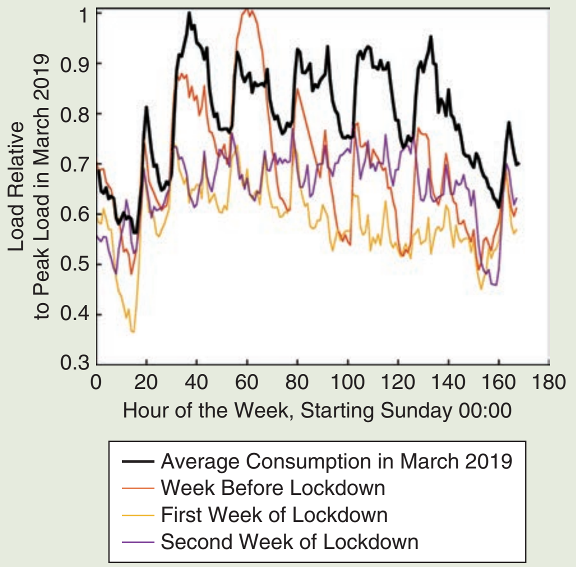

figure 3. The impact of the lockdown measures on Swiss electrical consumption.

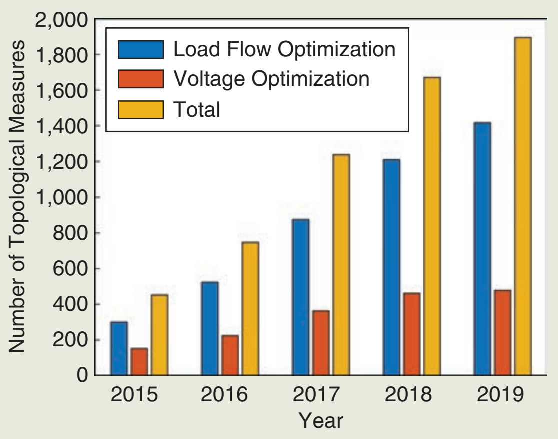

figure 4. The trend in topological measures as remedial actions.

Overall Trends in System Operation

The previous analysis of recent grid events revealed specific aspects of system operation that would benefit from a new operational philosophy. To evaluate the need for a new operational paradigm, one can also observe the overall trends in system operation in recent years. In this section, we present a simple analysis of the historical remedial actions in the Swiss transmission system taken against N–1 or voltage security violations. The remedial actions include topological measures to optimize either power flows or voltage profiles as well as generation redispatch. Furthermore, we distinguish between two types of redispatch actions: national and international redispatch. National redispatch actions are on Swiss power plants in response to internal issues in the Swiss transmission grid. On the other hand, international redispatch actions implemented by Swiss power plants are part of an international coordinated redispatch effort to resolve problems in either the Swiss or neighboring power grids.

Figure 4 displays the annual number of topological measures from 2015 to 2019 that were implemented either to optimize the power flows and relieve congestions or to optimize the voltage profile across the grid. A linear increasing trend is visible in both cases.

Figure 5 demonstrates the trend in redispatched energy from 2014 to 2019. Besides the total energy values, we present the breakdown into Swiss and international redispatches as well as generation decrease and increase actions. Even though it is hard to identify clear patterns for the various combinations, there is a general increasing trend for the total redispatched energy. A clearer trend exists in the frequency of redispatch actions, which is quantified by the number of days when at least one redispatch action was carried out (Figure 6). Furthermore, it is relevant to mention that the majority of redispatch actions was international (79% in terms of redispatch duration). This observation underlines the significance of TSO–TSO coordination as part of today's operational procedures, as explained previously.

Finally, there have been several recent grid situations where avoiding $N-1$ violations by applying separated busbar operations in several substations would lead to a low degree of connectivity in the transmission grid. In the worst case after a busbar operation, if a substation is connected to the rest of the grid with only one transmission line, the unexpected tripping of this line (e.g., a lightning strike) would cause the loss of the substation and the interruption of supply in the underlying distribution grid.

To summarize, the number of remedial actions against $N-1$ or voltage violations has been increasing over the last years, which increases the burden on the system operators in the control room. As mentioned earlier, remedial actions are mostly determined based on experience and rules of thumb derived from simulation-based approaches. We believe that system operation would benefit from a DSS that provides the operators with suggested remedial actions against $N-1$ and voltage violations. More importantly, the DSS could efficiently account for possible undesired side effects of actions against one problem (e.g., $N-1$ violation) on other operational criteria (e.g., voltage profiles and degree of transmission network connectivity).

Vision for a New Operational Paradigm

The analysis of recent grid events and trends in system operation demonstrate that improvements in the current operational philosophy, or even a new philosophy, are needed to ensure power system security in an ever-changing environment. In this section, we discuss elements that shall have a central role in a new successful operational paradigm.

Analytics and Visualization

Secure power system operation requires taking fast and effective actions under critical grid conditions. Typically, many alarms are displayed on the large monitor of a TSO control center in case of a grid event. In some cases, the system operators must visually process this information and identify the most important alarms. Analytics and artificial intelligence applied to real-time monitoring data can help classify the alarms into first priority (for example, alarms associated with the root cause of an event) and second priority (for example, alarms activated as a consequence of other alarms). Such methods, in combination with modern visualization approaches that, for example, display the alarms according to their assigned priorities, can help the operators obtain valuable insights into the ongoing grid conditions and increase their reaction speed. Moreover, algorithms running on monitoring data could help predict imminent grid events and provide recommendations of remedial actions to the operator to further reduce the reaction time.

Automated ex-post data analytics can help identify the root causes of past events of grid insecurity, learn from them, and better prepare for the future. For example, ex-post analytics can be applied to evaluate the effectiveness of historical remedial actions. A possible approach would start with assessing the accuracy of the congestion forecast tool and proceed with analyzing and classifying historical grid snapshots. More precisely, for each grid snapshot with security violations, the goal would be to determine the root cause such as 1) no congestion warning was issued due to poor forecast quality of generation and/or load; 2) congestion was correctly predicted, but the selected remedial action turned out to be inefficient; and 3) congestion was correctly predicted, but there was no available remedial action to mitigate the insecurity event. This analysis can help a TSO

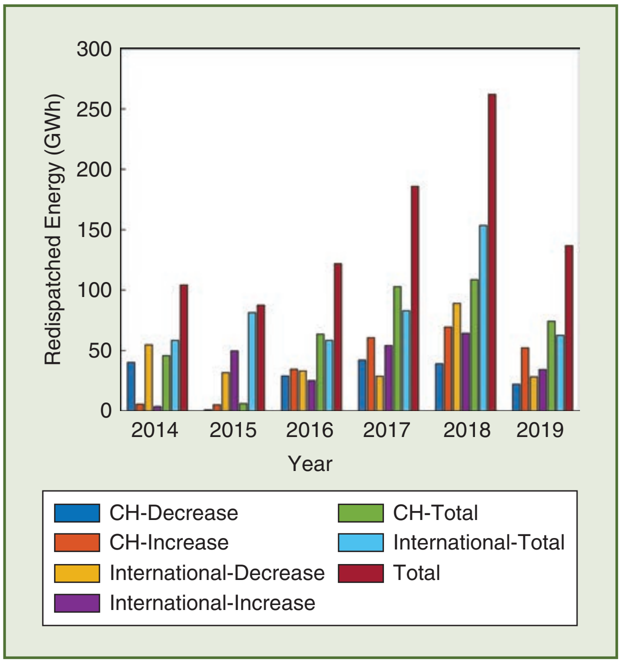

figure 5. The trend in redispatched energy due to remedial actions. CH: Swiss national.

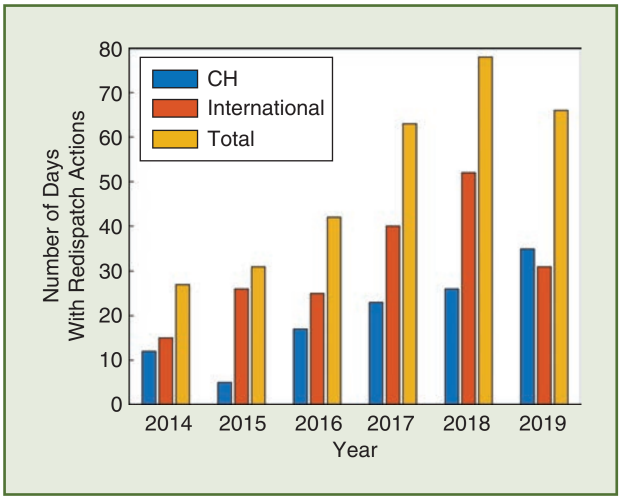

figure 6. The trend in the number of days per year when redispatch actions were implemented.

decide where to devote more resources to improve energy security, for instance, by upgrading the congestion forecast tool or by investing in a DSS for the optimization of remedial actions.

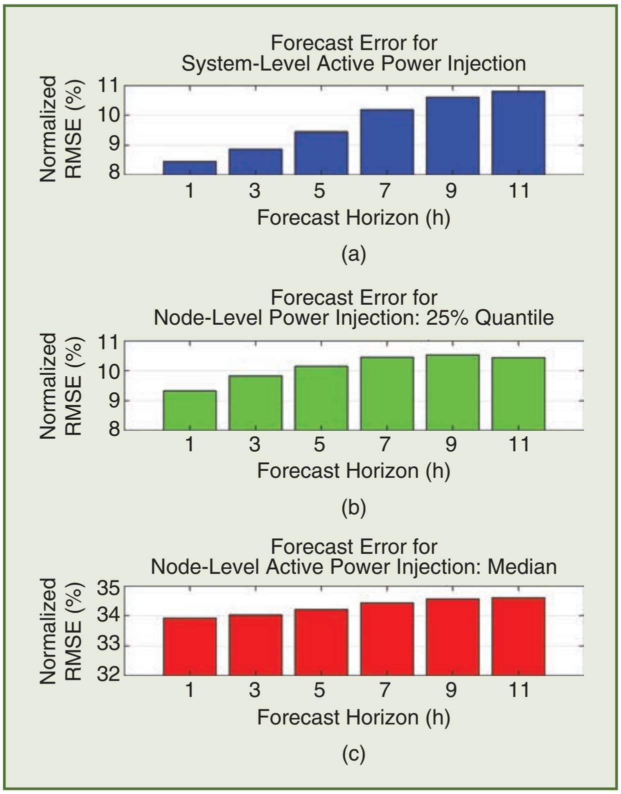

figure 7. The dependence of prediction quality of net active power load on the forecast horizon.

Currently, Swissgrid is working on such ex-post analytics, and here we present some preliminary results from the assessment of the net load forecast. As part of the intraday congestion forecast process, a tool generates predictions of the aggregate net load in the Swiss system as well as of the net load at each transmission bus. Specifically, the bus-level forecasts are obtained based on the aggregate forecast with the usage of predetermined load allocation factors. The predictions are updated every hour and have a forecast horizon in the range of 8–24 h, depending on the time of the day.

Figure 7 displays the normalized root-mean-square error (RMSE) of the predicted net active power load for six increasing forecast horizons. The errors are computed for the period from January to April 2020. In Figure 7, (a) is for the aggregate net load, whereas (b) and (c) correspond to bus-level predictions. Specifically, Figure 7(b) shows the RMSE's 25% quantile, and Figure 7(c) plots the median value, both computed across all buses. Although the error generally increases with the forecast horizon, the differences are rather small, and this trend is less pronounced for bus-level predictions. In contrast to the relatively low errors for the aggregate net load, the median of the bus-level RMSEs is unexpectedly high, mostly due to shifts and/or biases in the predicted time series for some of the buses. This may be partly because of a significant amount of production resources in and/or a meshed topology of the underlying lower-voltage grids.

Furthermore, Figure 8 illustrates the ratio of RMSE for forecasts obtained with a 1-h lead time over those with a 7-h lead time. The smaller the ratio, the better the relative performance of 1-h-ahead forecasts. While, for most transmission

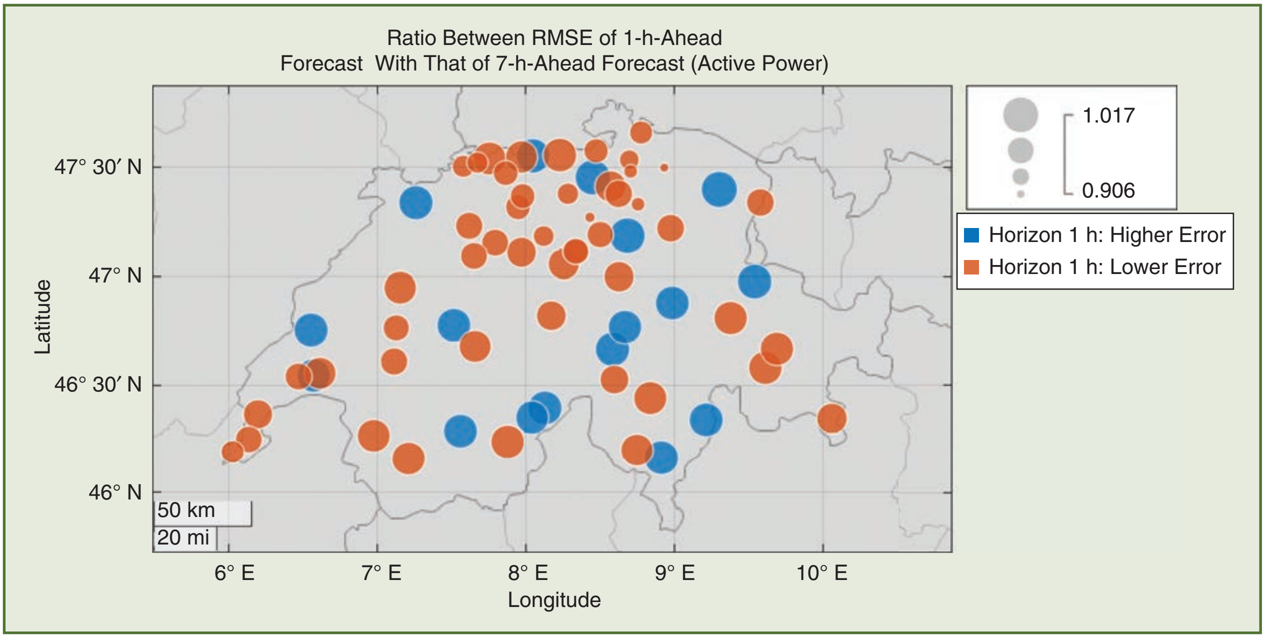

figure 8. The geographical distribution and classification of transmission buses with regards to the relative accuracy of 1-h-ahead and 7-h-ahead forecasts.

buses, the 1-h-ahead forecasts are better (orange circles in the figure), there are also several buses with 7-h-ahead forecasts with higher accuracy than the 1-h-ahead ones. Future investigations can focus on tracing the cause of these imperfections and improve the performance by either optimizing the load allocation factors applied in the forecast model or switching to a new forecasting approach.

By splitting the data set into the periods before and after the lockdown in Switzerland as a measure against the COVID-19 pandemic, we can analyze the effect of the lockdown on the forecast quality. As seen in Figure 9, the RMSEs are significantly lower in the prelockdown period, especially for longer prediction horizons. This can be partly attributed to the fact that the forecasts have a strong seasonality component, which resulted in an overestimation of the net load demand in the weeks right after the lockdown.

DSSs

The second key aspect of the future operational philosophy is an extensive usage of DSSs to assist the personnel involved in core TSO tasks in decision making. As detailed in Figure 10, the four core TSO activities to ensure system security are 1) grid reinforcement and expansion, 2) maintenance scheduling for transmission assets, 3) congestion management, and 4) control actions in real-time system operation. Today, these four activities typically follow a chronological sequence and interact in a mostly unidirectional way from left to right, as depicted with the gray arrows in the figure. We believe that higher effectiveness across the entire activity chain can be achieved if the degree of bidirectional information flow increases, namely if there is the consideration of activities closer to real time within the ones in the planning phase (indicated with black arrows in Figure 10).

Within this general vision, we specifically propose an approach to integrate the maintenance scheduling (outage planning) and congestion management (congestion forecast, security analysis, and remedial actions) phases of the activity chain. Today, Swissgrid's operational planning team receives maintenance plans from transmission asset owners (ownership of Swissgrid), generation asset owners, distribution asset owners (only to a limited extent), and transmission assets of neighboring TSOs. Information comes through

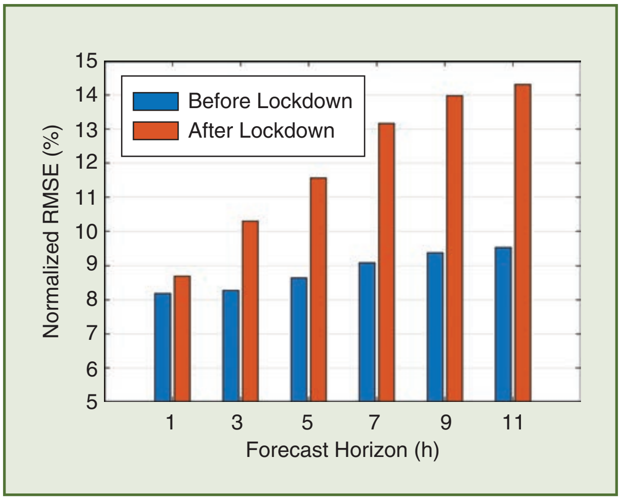

figure 9. The effect of anti-COVID-19 lockdown measures (applied 16 March 2020) on the intraday congestion forecast error.

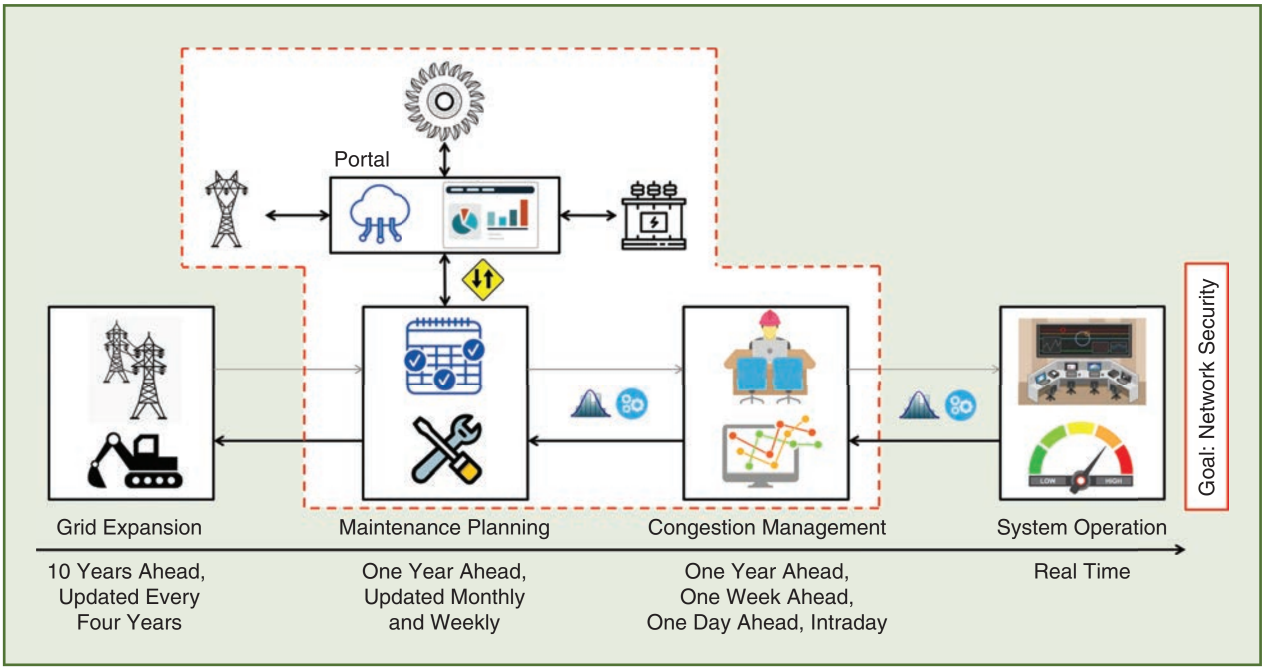

figure 10. Strengthening the links among the core TSO activities will enhance network security with a focus on maintenance planning and congestion management. (This image has been designed using resources from Flaticon.com.)

different communication channels ranging from dedicated platforms to emails and phone calls. It then is the task of the operational planning team to verify the feasibility of the received maintenance schedules based on the congestion forecast and security analysis (at various time scales: year ahead, week ahead, and day ahead).

In case of anticipated *N* or *N*–1 violations, three types of measures are investigated: topological actions, generation limiting and redispatch, and maintenance rescheduling. In the latter case, coordination with the respective asset owner is required until an alternative solution is found, and then security analysis needs to be repeated to check the measure's effectiveness. This iterative process is the result of the sequential coupling between maintenance planning and congestion management. Notably, if anticipated congestion can be avoided by either a real-time topological action or by rescheduling the maintenance of a grid asset, the former is often preferred due to the complexity in maintenance rescheduling among several asset owners and their maintenance service providers.

To improve operational efficiency and security of supply, we envision an integrated approach to optimize the maintenance schedules of a control area's transmission grid assets while considering possible congested network elements in system operation as well as the maintenance needs of generation and distribution grid assets. A comprehensive maintenance scheduling tool would comprise maintenance periods as decision variables for four types of assets: 1) transmission assets of the control area, 2) DSO assets, 3) generation assets, and 4) transmission assets of neighboring control areas. Since the specific maintenance requirements of points 2)–4) are not known to the TSO of the given control area, we propose that DSOs, generation companies, and neighboring TSOs submit a list of preferred maintenance windows as well as blocking periods when no maintenance work is possible for their assets.

As indicated in Figure 10, the submission of preferences can be enabled by a portal that all involved parties can access. The best maintenance window for each asset is then determined while ensuring network security in case of contingencies and satisfying the submitted preferences as much as possible. In this way, the TSO's operational planning team automatically obtains a maintenance schedule that minimizes the need for remedial actions against grid insecurity. This is a pragmatic approach placed halfway between today's industrial practice where generation and distribution asset owners submit fixed maintenance schedules to the TSO and idealized academic approaches where generation and transmission assets with distinct ownerships are co-optimized. Figure 11 presents an illustration of the envisioned approach for integrated maintenance scheduling and congestion management and contrasts it with today's practice.

From a mathematical point of view, this is a complex optimization problem due to the presence of integer decision variables (maintenance schedules, topological remedial actions, and so on) and various nonlinearities, especially if an ac power flow model is used to capture voltage violations. Moreover, it is a large-scale problem due to the hundreds or thousands of buses and transmission lines and the consideration of many contingency scenarios. Further, as revealed by the analysis of some historical grid events, it is sometimes important to include models for the distribution grid in the study, which further increases the problem size. Such a large-scale, mixed-integer, nonlinear, and nonconvex optimization problem is practically impossible to solve to full optimality in a reasonable amount of time and with realistic computational resources. Nevertheless, for practical applications, a good feasible solution that satisfies time and computational constraints would be sufficient.

Various methods have been proposed in the scientific literature to optimize the maintenance scheduling of power grid generation and transmission assets (in a separated, sequential, or joint manner). The methods to solve the resulting mixed-integer program can be generally classified into mathematical programming, heuristic approaches, and combinations of these. Early mathematical programming approaches were based on dynamic programming that, however, turned out not to be scalable due to the curse of dimensionality. More recent approaches rely on branch and bound-based mixed-integer program models often enhanced with decomposition techniques (mostly Bender's decomposition or Lagrangian relaxation). Such approaches typically use a linearized dc power flow model, thus resulting in mixed-integer linear programs. A large variety of heuristics has been applied in the maintenance scheduling problem, including genetic algorithms, particle swarm optimization, simulated annealing, cuckoo searches, electro search algorithms, and so on.

We believe that a hybrid approach is needed to efficiently tackle this problem at scale, which combines elements from mathematical optimization, heuristic optimization, artificial intelligence, and customized approximations based on operational experience. An example of a hybrid approach would be applying first a heuristic to provide a set of initial feasible solutions and then using these to initialize branch and bound-based algorithms executed in parallel to obtain local optima in the neighborhood of the initial feasible solutions. Such an approach would combine the strength of heuristics in efficiently exploring a vast and nonconvex search space with the guarantee of mathematical programming to return locally optimal solutions.

Another possibility would be to use heuristics for the discrete variables and mathematical programming for the continuous ones, which could be done either in two steps or iteratively. For instance, one could use heuristic optimization until the discrete variables converge and then switch to gradient-based optimization for the remaining continuous variables. Alternatively, one could decompose the problem into an outer loop optimizing over the integer maintenance decisions (solved with heuristics) and an inner loop optimizing over remedial actions [basically, a

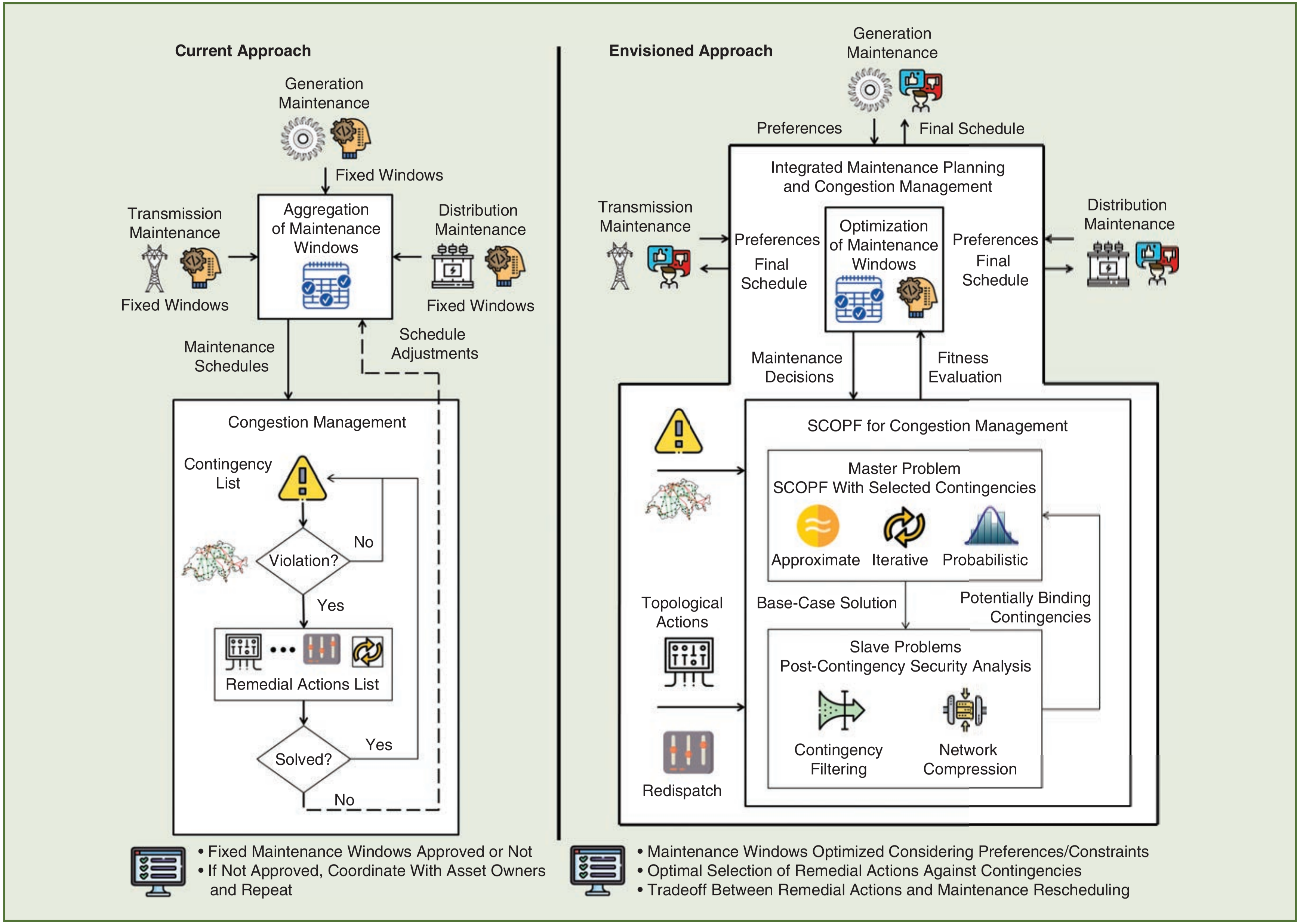

figure 11. Today's approach and future vision for coordination between maintenance scheduling and congestion management. (This image has been designed using resources from Flaticon.com.)

security-constrained optimal power flow (SCOPF) solved with mathematical programming].

Customized approximations aim at reducing the size and/or complexity of the optimization problem by incorporating operational experience and knowledge about the system. Ideally, an industrial-grade DSS for integrated maintenance scheduling and congestion management would combine multiple approaches that have shown good performance in the literature, such as contingency filtering, network compression, and adaptive linearization. The first two are typically implemented simultaneously, where contingency filtering selects the contingencies that are expected to be binding at the optimal solution, and network compression reduces the size of each postcontingency network. Adaptive linearization could be employed to simplify the power flow equations of selected lines in formulations that use an ac network model. For instance, lines with frequent N–1 violations or voltage violations at the terminal buses are modeled with ac power flow equations, whereas a dc model could be used for lines that hardly ever experience violations.

Needless to say, the approach presented here can be extended in various ways to account for additional issues identified from the analysis of historical grid events. For example, constraints on the degree of network connectivity could be modeled in the "SCOPF for Congestion Management" module of Figure 11 to avoid creating weak grid links due to remedial actions. Also, customized measures, such as the minimum production product discussed earlier in the "Historical Grid Events in the Swiss System" section, can be obtained as the outcome of such an optimization-based approach by introducing the appropriate modeling variables. Finally, this approach could provide the basis for a more compressive (possibly probabilistic) medium-term energy security planning process that integrates outage planning, congestion management, and adequacy planning with consideration of storage levels of hydro dams and market conditions.

Summary

In this article, we have addressed the challenging task of maintaining power system security from the perspective of the Swiss power system. We started with a review of the distinctive characteristics of the Swiss electricity grid and an explanation of today's practices for maintenance scheduling, operational planning, and real-time system operation. Despite the success of these practices, we argue that enhancements or even a new operational paradigm are needed in the future to cope with the constantly changing boundary conditions of the power grid. Based on a few recent grid events and historical trends in power system operation, we identified aspects of particular importance. These include representation of subtransmission and distribution grids in planning and operation, better coordination of maintenance scheduling across different power system assets, preventive measures against voltage violations, and consideration of the effect of topological actions to the level of network connectivity. In response, we presented two key aspects of a new operational paradigm that would help enhance system security, namely data analytics and DSSs.

Specifically, we outlined an integrated approach for the traditionally time-separated activities of outage planning and congestion management. The approach enables a combined consideration of the maintenance needs of transmission, distribution, and generation assets in the planning phase while increasing the margin for preventive interventions against contingencies closer to real-time operation. To realize the envisioned approach, methodological innovations in the field of SCOPF are needed, including hybrid approaches combining ideas from mathematical and heuristic optimization.

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For Further Reading

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