Security Assessment for higher loaded power system operation to 2030

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Abstract

The objective of this paper was to introduce the concept of a novel assessment process for maintaining operational security in grids with high transmission loading. Curative measures are included in the process. The proposed approach combines Steady-State Security Assessment (SSSA) and Dynamic Security Assessment (DSA) to address future challenges of a changing generation environment and innovative concepts in system operation. Operational security of power systems with DSA as state of the art is introduced. An expert evaluation for future system limits was carried out to reveal the demand for new processes in system operation. The final process represented a joint optimization of dynamic and static security assessment including a feedback loop from DSA to SSSA enabling curative system operation in future grids with the target year 2030.

1 Introduction

The integration of renewable generation into the power system combined with a delayed grid expansion will cause an increase of transmission loadings. Against this background, automated system operation with curative and system stabilizing measures can help to maintain a high level of security of supply. In addition, by optimizing the utilization of the grid, it can also be operated more economically and redispatch can be avoided. A (N-1)-secure operation can be ensured even in fault and outage situations by including curative measures, power flow controlling equipment and system automations for higher utilized and loaded grids [1]. This requires the use of innovative system operating as well as new operational planning processes to maintain consistent system reliability.

The assessment of system security is a key objective for system operation and planning and can be evaluated using Steady-State Security Assessment (SSSA) [2] and Dynamic Security Assessment (DSA) [3]. A higher thermal load of the grid with correspondingly high operating currents, also has an impact on grid stability. This can be countered with grid-supporting measures. High voltage direct current (HVDC) systems, grid booster (GB), flexible AC transmission systems (FACTS) and phase shifting transformers (PST) can be used primarily as curative measures. With modern control and information technology and suitable selection of measures, they can also have a stabilizing effect.

The steady-state contingency analysis (CA) refers to the evaluation of operational boundaries and compliance with the operating voltage bands. However, an evaluation of curative measures is necessary in order to achieve automated system control and higher loading of the power system. Additionally, the power systems needs to be evaluated with regard to stability aspects [4].

This contribution describes an innovative assessment process for future system operation as Decision Support System (DSS) [5] to asses system states and furthermore to select stabilizing measures. The stability limits that make such a process necessary are schematically depicted and described for the scenario of highly utilized grid states for the system structures for the target year 2030. The current status in terms of stability assessments is presented in the context of future challenges in system operation. Subsequently, an assessment process is described in detail as a combination of SSSA and DSA in future transmission system operation ensuring (n-1)-secure and stable grid operation. A distinction is made between curative and thus load flow controlling and stabilizing measures

2 Operational security

Secure system operation implies that the operating criteria and boundaries are respected at pre- and post-contingency conditions and is characterized by thermal limits, voltage constraints, short-circuit current, frequency and stability limits [6]. Steady-state power flow and time-domain dynamic simulations are used as tools to ensure security as shown in **Figure 1**.

Remedial or curative actions [1] are applied as measures in order to maintain operational security by returning the system to a normal state while fulfilling the (N-1)-criterion and operational security limits after contingencies.

Security assessments have historically been performed in an offline planning environment where the steady-state and dynamic performance of near-term predicted system conditions are determined [7]. Online data can serve as well

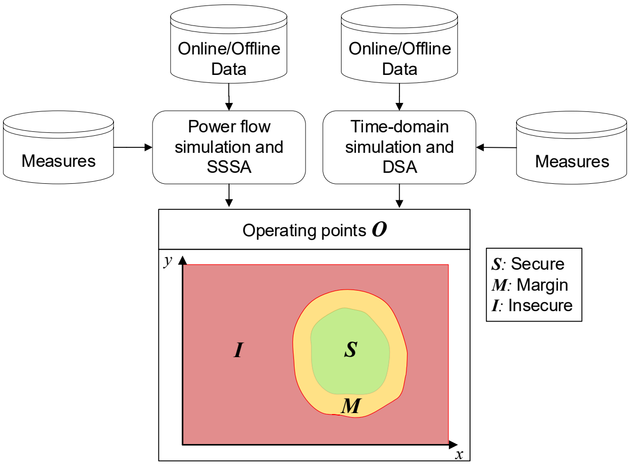

Figure 1 Determination of secure operating points

as offline data for the implementation. Due to the technical and computational effort required for more complex assessments, such as DSA, it is state of the art to estimate system operating limits well in advance (offline) [8]. The most critical conditions and contingencies, even if most of them are unlikely to occur, are determined to estimate a margin M between the secure operation set S and the insecure set of operating points I. This ensures a sufficient margin to operating limits and stability limits for the new operating point in outage situations and disturbances. The sets S, M, I are disjoint and form the universal set O to which applies:

$$S \cap M \cap I = \emptyset \quad (1)$$

$$S \cup M \cup I = O \quad (2)$$

$$O := \{S, M, I\} \quad (3)$$

P, Q, V and I are the active power, reactive power, voltage and current operating points of O:

$$\{P, Q, V, I\} \in O \quad (4)$$

The evaluation of a grid status with regard to the operating limits is carried out by the system operators on the basis of static system limits. These are either temporarily or permanently admissible [9].

The so-called *Permanent Admissible Transmission Loading* (PATL) defines the permissible continuous operating current or power over a branch or element in the grid. If the limits are complied with, operation is permissible for an unlimited time. In opposite to this, *Temporary Admissible Transmission Loading* (TATL) describes a load that is only temporarily permissible. The TATL values can, be defined with a fixed percentage offline, e.g. 115% of the PATL for 15 minutes, or calculated specifically for the respective network branch. Accordingly, PATL and TATL are set so that no thermal overloads occur, unwanted protection trips are avoided and no loss of system stability occurs.

Future developments require online approaches and a stronger integration of DSA into the process with a focus on higher grid utilization and upcoming stability challenges.

2.1 Power system stability

Power System Stability as part of operational security describes the capability of a power system to regain a steady state after a disturbance and can be classically divided into *Rotor Angle-*, *Frequency-* and *Voltage Stability* with its respective sub-definitions as illustrated in **Figure 2** [4]. This definition can be extended to include the terms *Converter-driven* and *Resonance Stability* according to [10].

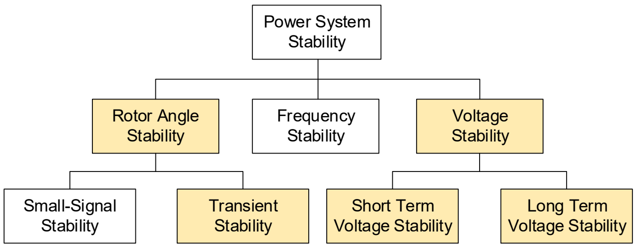

Figure 2 Classification of the relevant stability aspects [4] for higher grid utilization

A change of the system eigenvalues is not to be expected by an increased utilization, which is why the *Small Signal Stability* is not in the focus for this scenario. *Frequency-Stability* is also not directly addressed. Both stability areas are most likely to be affected by the changing generation environment in the future. Higher utilization primarily addresses the system-wide *voltage-* and the local *transient stability* as part of *rotor-angle stability*, due to the reactive power demand and increasing power angles [11] [12].

2.2 Dynamic Security Assessment

To guarantee all aspects of security, analyses must be performed including the thermal loading of system elements as well as power system stability. Dynamic Security Assessment (DSA) can be used to evaluate power system stability. It can be subdivided in offline and online DSA. Both are used to estimate system operating limits with respect of power system stability. Time-domain simulations on the basis of a dynamic reference model such as the Dynamic Study Model (DSM) [13] are executed on demand or for stability studies within DSA. Resulting stability limits are statically considered in system operation. Power flow simulations for contingency analysis (CA), continuation power flow (CPF) and optimal power flow (OPF) are used in operational planning and system operation (SO) and are state of the art, as depicted in **Figure 3**.

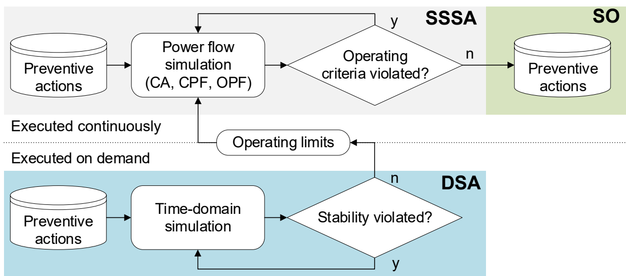

Figure 3 State of the art of security assessment

Offline DSA for operational security: Offline methods are usually assigned to grid- and operational planning. On the basis of a reference grid equivalent (grid planning) or expected state (operational planning), measures are evaluated with regard to operational security. Within operational planning, the impact of system dynamics can be taken into account by means of static limits.

Online DSA for operational security: Online methods are used for operational planning or grid operation. The power system operation can evaluate the current grid conditions in real-time, using snapshots. Near real-time analyses, which are usually between the current grid state and the first intra-day congestion forecast (IDCF) provided by operations planning, are usually assigned to grid operation. Forecasts that go further into the future, e.g day ahead congestion forecast (DACF), are assigned to operational planning. Online procedures have the advantage that they take into account the current grid state from the control room, but are limited by time constraints in operation.

2.3 Stability Limits

At present, the dynamic stability limits are still mostly not critical, since the steady-state limits (generally thermal limits) are generally below them. Impending bottlenecks are eliminated with preventive remedial measures, which are determined in the operational planning process. By utilizing the thermal reserve, e.g. by dynamic line rating (DLR) or high temperature conductors (HTC), the operating limits can be temporarily or permanently increased for the purpose of higher utilization. However, the stability limits are not raised if the line or equipment parameters remain unchanged. Increasing transmission powers P_{Tr} and the decommissioning of conventional generation plants with the associated decrease in system inertia I and short-circuit power S''_{sc} in combination with curative measures may even cause a decrease in stability limits in the future. **Figure 4** schematically illustrates a possible development of the systemic limits.

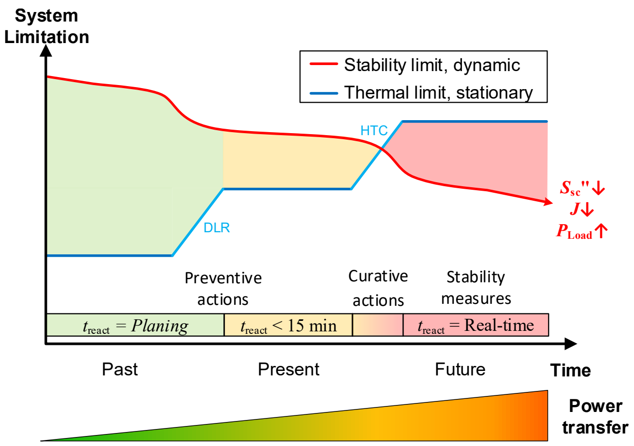

Figure 4 Visualization of future system limitations

Disturbances can be handled with curative measures in time ranges within the thermal time constants of the equipment ($t_{\mathrm{react}} < 15\,\mathrm{min}$). In large-scale highly loaded grids, stability limits may be below the (thermal) operational limits of equipment during disturbances (e.g., (n-1) outage). These must be respected before and after unexpected events to avoid instabilities and thus blackouts. To prevent instabilities caused by transients and power flow adjustments, stabilizing measures must be initiated in real time in case of limit violations.

3 System Operation to 2030

Current system operations only consider the initial grid state and the preventive (n-1) operating point. The concept of (temporary) higher utilization, combined with curative system operation will result in one additional system state that need to be subjected to a security assessment as shown in **Figure 5**.

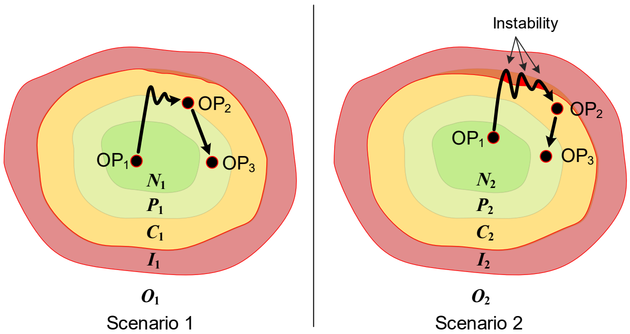

Figure 5 System states for higher grid utilization

Basically, the same system with different initial states is assumed for both scenarios defining the universal sets O_1 and O_2. The difference between the sets is that the initial state can impact the stability limits and therefore the set I_i of insecure operating points varies. The stability limits are not static. The universal sets of O_i are defined for curative system operation. Compared to Figure 1, the security margin to the insecure or unstable operating domain is now described by the quantity C_i of the curative operating points after contingencies. C_i implies curative (n-1) secure operation. The set of secure operating points (S in Figure 1) is divided into the subsets N_i for nominal operation and P_i for operating points that are secure for preventive (n-1) operation and after curative actions.
The sets N_i, P_i, C_i, I_i are disjoint again and form the universal set O_i to which applies for $i \in \{1,2\}$:

$$O_i := \{N_i, P_i, C_i, I_i\} \tag{5}$$

The two scenarios can be described as followed:

Scenario 1: secure grid operation The system is initially operated within the secure area N_1 (OP_1). A contingency drives the operating point out of the nominal operating into C_1 (OP2), where a temporarily operation is permitted. Curative measures return the system state back to secure operation in P_i (OP3). The change of the operating points and the associated transients do not lead to stability issues. A (quasi)-stationary analysis of the system is sufficient to ensure secure system operation.

Scenario 2: insecure grid operation Scenario 2 implies a higher utilized state within the secure area N_2 (OP1). A contingency drives the operating point out of the nominal operating area into C_2 (OP2), while the transients caused by a sudden change of state let OP2 pass through the insecure area I_2. This may result in instabilities that must be corrected by stabilizing measures in real time or even before the disturbance occurs. Otherwise, the secure system operation is endangered. A (quasi)-stationary analysis of the system is not sufficient to ensure secure system operation. Time-domain based analysis must be performed.

Three relevant sections can be outlined:

1. Higher utilized initial grid state, where PATL has to be considered (OP_1).
2. Temporarily permissible contingency variant, where TATL has to be considered (OP_2).
3. Higher loaded final state after application of one or more curative measures, where TATL during measure and PATL for steady-state have to be considered (OP_3).

In the concept of curative system operation, the contingency variants (2) are regarded as temporarily permissible operation as long as curative measures are available to return the system to a value below the PATL. The final state (3) is not necessarily (N-1)-secure, since this depends on the (re)availability of the curative and preventive measures. The system operation must restore (N-1)-security rapidly.
Within the scope of the security calculation, each of the system states (1) - (3) can be subjected to a security assessment. A dynamic (n-1) security calculation is only suggested starting from the initial higher-loaded grid utilization case (1) respectively the transitions to (2) and (3). A separate security assessment with contingency analysis of the states (2) and (3) leads to computationally complex (n-2) calculations, especially for dynamic time-domain simulations.
A steady-state approach only considers the power flow, currents and voltages before the disturbance in nominal operation OP_1, during the failure situation OP_2 and the curative action to restore (n-1) secure operation (OP_3). Temporary violations of the stability and operating limits, however, are only detected in a dynamic time-domain analysis. In case a violation is detected, stabilizing measures can be taken which damp the transients or raise the stability limits. A mere steady-state assessment is no longer sufficient for system operation in view of the changing system limits and operation concepts. A separated assessment of the system stability as shown in Figure 3 is not suitable for the detection of operational security violations and the appropriate selection of measures. Static limits for stability cannot assure enough margin to insecure system operation. The stability limits have to be estimated dynamical and scenario based. The steady-state and dynamic assessment must be combined to address the increasing challenges. Novel approaches for the operational security assessment and measure selection are necessary.

3.1 Security assessment

In order to detect and counteract possible stability violations of a curative system operation, dynamic considerations must be included in future security assessments and system operations. The objective of the assessment process shown in **Figure 6** is to approve a given grid utilization case for a defined list of contingencies in terms of operational security.
The process is integrated into the system operation (green) with a combination of SSSA (gray) and DSA (blue) and analyses contingencies for different grid utilization cases. A security assessment evaluates the operational limits with focus on power system stability. If necessary, the simulation and assessment is repeated with the inclusion of stabilizing measures.

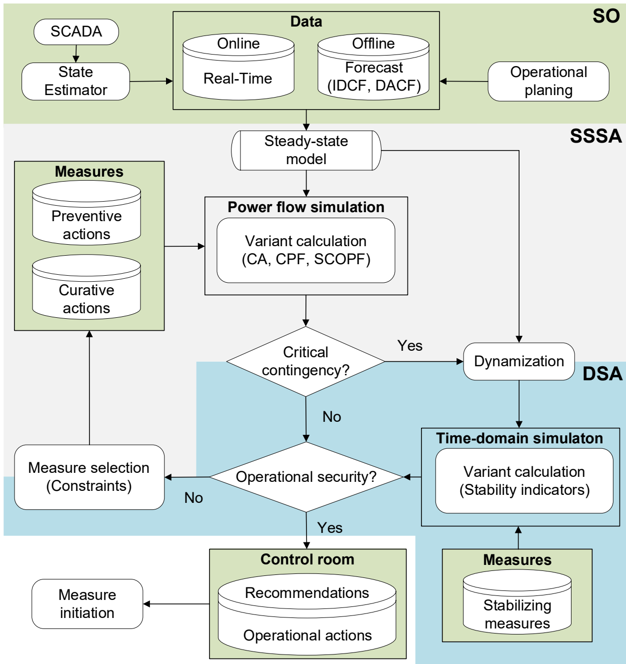

Figure 6 Combined SSSA and DSA process

The initial grid utilization case can be provided by a snapshot from the State Estimator or as offline data from the operational planning. The resulting grid model is initially stationary and has to be analyzed dynamically.
For the DSA, the stationary grid utilization case is converted into a dynamic grid model. It is possible that a complete approval of certain grid situations is only possible by using curative (stationary) and, if necessary, additional stabilizing (dynamic) measures. The selected measures are presented to the system operation as a recommendation for action. A grid scenario that has not been dynamically approved is returned to the steady-state assessment and the process is repeated.
Based on possible stability violations, constraints for the steady-state optimization of the curative measures can be derived. If grid states exist that cannot be classified as secure even with the application of curative and stabilizing measures, the initially given grid utilization case cannot be enabled for operation. In this case, the process must be repeated including preventive actions as measures.

The assessment process can be subdivided in three sequences that repeat cyclically:

- Data management
- (Steady-state/) Time-domain based RMS simulations and security assessment
- Selection of measures

3.1.1 Data management

The assessment process starts with a grid utilization case to be investigated. The case can be committed from the control room (as a result of the state estimation) or from planning data such as Two-day ahead congestion forecast (D2CF), Day ahead congestion forecast (DACF), Intraday congestion forecast (IDCF). After the grid utilization case has been evaluated and approved by the SSSA, selected contingencies of the grid utilization case must be evaluated dynamically with time-domain based RMS simulations (DSA). Since the grid utilization case is a stationary data set, it must be dynamized as described in [14]. For this purpose, mainly equipment, models and controller data are added. Depending on the nature of the underlying data set, the quality and thus the information of the dynamized grid model also differ. One aspect of this low data quality concerns the lack of consideration of reactive power, since stationary preview data sets are often configured for active power flows only. However, reactive power is also essential for stability studies.

In addition to the initial processing of the input data, data evaluation and preparation also takes place after the security assessment. In subsequent operations, the corresponding conclusions and recommendations for action must be made available to the system operator or the operations planner in a transparent format as part of a possible Decision Support System (DSS) [5].

3.1.2 RMS simulations and security assessment

The dynamized data set is analyzed for stability using a large number of RMS simulations. For this purpose, a selection of fault scenarios must be calculated and evaluated automatically. *Long-term voltage stability* should first be evaluated (quasi-) steady-state and can be considered as part of the SSSA. To limit the number of cases and thus the computational complexity, a steady-state and subsequently a dynamic risk evaluation must be carried out to identify critical contingencies for stability analyses. A scenario is then defined on the basis of the fault location and the fault case. Stability indicators are then used to evaluate each contingency assessing whether the grid utilization use case is also stable for various disturbances. Likewise, a qualitative conclusion about the robustness of the system state can be made on the basis of the margins of the indicies, which vary usually between 0 and 1.

3.1.3 Stability measures

The grid utilization case is approved if no violation of operational security (SSSA and DSA) is detected after the initial security assessment. If a violation occurs, i.e. a stability criterion is violated or the protection would be triggered, a corresponding stabilizing measure is selected and a further run consisting of DSA is started. Stabilizing measures could include releasing withheld reactive power reserves, adaptive controller adjustments (e.g. droop coefficients, power system stabilizer, control modes of converters) and fast curative actions. There are two possibilities to select stabilizing measures:

1. Successive selection of measures until there are no more findings, then approval of the data set with recommendation of the measure(s).
2. Processing of all measures and selection of the most suitable or best measure(s)

The first approach leads to lower calculation times, but has the consequence that the best measure is not necessarily selected. The second approach provides an overview of the available measures and the respective impact of each measure. Based on the stability indicators, one or more measures can then be recommended. The selection of measures is thus based purely on their stabilizing effect.With both approaches it is also possible to combine measures arbitrarily, but this significantly increases the computational effort and requires a corresponding parallelization. In certain situations, however, it may be possible that a system state is only stable by combining several measures. If the grid utilization case is classified as critical despite existing measures, grid operating adjustments are necessary. For this purpose, corresponding constraints have to be returned to the SSSA. New operating points have to determined solving optimization problems in the following form:

$$\begin{aligned} \underset{x}{\text{minimize}} \quad & f(x) \\ \text{subject to} \quad & g_i(x) \leq 0, \quad i = 1, \ldots, m \\ & h_j(x) = 0, \quad j = 1, \ldots, p \end{aligned} \tag{6}$$

where $f(x)$ is the objective function for stability improvement to be minimized, $g_i(x)$ are the inequality constraints to be adapted and $h_j(x)$ are the equality constraints. It is essential to know which stability criteria have been violated in which scenario to select effective objective functions and constraints.

3.2 Protection Security Assessment

In addition to thermal and stability limits, protection is an important aspect of the limit estimation in the system security calculation. Without protection security, i.e. the avoidance of protection over-function, secure grid operation is not possible.

The state of the art procedure is the definition of a fixed protection limit current up to which faulty pickups during operation are to be excluded. It results from the resistive reach setting of the distance protection devices required for minimum sensitivity and the assumptions made. German TSOs agreed to an assured value of 3730 A, with up to 4000 A achievable according to current procedures [15]. More profound changes in the protective device algorithms in the form of modified impedance measurement or new fault detection algorithms may further increase this value in the future. Another way to increase the loadability limit imposed by protection is to represent it more adequately than in terms of a pure current value. This can be done by additional criteria such as voltage and phase angle or by including the impedance polygon in the security calculation. Additionally, optimizations of the shape of the load blinder can allow for higher load flows [16].

Dynamic or transient processes are currently only taken into account via safety factors in the protection limit or by using power swing blocking. In the future, the consideration of protection systems in the dynamic security assessment can contribute to optimized protection security with maximum utilization of loadability potential.

4 Conclusion

Future system and operating developments are increasing the requirements on transmission grids. As a result, the validity of purely steady-state security assessment (SSSA) and static system limits for security assessment is severely limited and should be replaced by a scenario based evaluation of system limits for critical contingencies. A higher loading of the electrical power system requires a combination of stationary as well as dynamic analyses in the security assessment process. The assessment process presented in this paper provides a solution for the transmission system operation to evaluate future grid operating points while maintaining power system stability. An integration of the process into the system operation enables curative operation and operational security from a system stability point of view. The process ensures that a steady-state and dynamically approved grid utilization case is also permissible for contingencies in highly utilized grids. For the implementation of such a process, risk assessments are useful to keep the computational effort of the DSA low and to minimize the simulations of grid situations that are not critical and have a low probability of occurring. In the future, the use of pattern recognition and machine learning algorithms may be considered to reduce the computational complexity both dynamically and steady-state in the power system operation.

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