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Early Detection and Mitigation of the Risk of Blackout in Transmission Grid Operation

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SUMMARY

In the aftermath of the wave of blackouts that affected utilities in recent years, new operating policies started to require system operators to compute stability limits for current and near-future operations processes to foresee whether the transmission loading progresses, or is projected to progress, towards states where voltages may collapse, units may lose synchronism, or other instability phenomena occur. This is far from being a trivial exercise. On the one hand, this is because instability in many cases develops almost instantly. Therefore, operating states that are vulnerable to instability must be prevented and the risk of instability must be predicted. On the other, the operating conditions change continuously, and the only way for the prediction to be timely and accurate is for the assessment to be performed in real-time on a continuous basis and for the distance to instability to be monitored.

In the context of system operations, the traditional approach has been to compromise between the depth of the stability calculations and the speed of the stability calculations. But the need to compromise between depth and speed of the stability calculations can be reduced if a more sensible approach is deployed which encompasses a balanced mix of rapid, instantaneous assessment predicated on processing and interpreting PMU data, fast, yet somehow approximate real-time stability tools running in tandem with state estimators, and precise, although more time consuming, detailed stability calculations.

This paper describes such a comprehensive approach to blackout prevention and mitigation, which integrates field-proven stability tools with newly developed approaches that currently undergo pilot field installations. The method brings under an all-encompassing umbrella both the technology to detect system states where voltages may collapse and units may lose synchronism and the ability to recommend preventive and/or corrective strategies. As an added benefit, the approach documented in this paper is clearly aimed to be used in real-time in a transmission (super-) grid control center environment integrated with or closely linked to the SCADA/EMS. Theoretical considerations and practical aspects that help understand this technology are also included, along with implementation examples that illustrate its deployment in actual control centers.

KEYWORDS

Blackout – Prevention – Risk – Mitigation – Realtime – Stability – Assessment – PMU – Wide Area Monitoring - Synchrophasors

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Basic concepts of Detection and Mitigation of the Risk of Blackout

An important goal of dynamic security assessment is to determine whether the system can withstand a set of major, yet credible, contingencies. An equally important goal is to evaluate the risk of instability if the system approaches a dangerous state slowly as a result of:

- Small topology and/or load changes accompanied by slow bus voltage changes that may trigger a voltage collapse, and/or
- Gradual load increases that may eventually cause one or several generators to lose synchronism.

Instability in a power system may also be triggered when attempting to transfer large MW blocks to compensate load increases and/or generation outages in certain system areas by increasing the generation somewhere else. Other types of instability take place when units lose synchronism because of self-oscillations. At the present time there is no unified methodology to handle all aspects of stability. The terminology is not unified, either, and terms like transient stability, small-signal stability, voltage stability, steady-state stability, and so on, denote tools and models tailored to usually handle only one of the multiple physical phenomena associated with instability.

The problem complexity increases when assessing vast interconnected grids because of the sheer amount of data, the potentially large computing times, and the technical skills needed to interpret the results. But even if computational speed was achieved and the stability calculations were performed in real-time, or, perhaps, online, i.e., with real-time input but slower than the real-time process, there still would be a need to develop indicators encapsulating relevant and/or critical information in a format that can be easily interpreted and understood.

Blackouts do not happen suddenly and without prior signals of distress. Unplanned transmission outages, decaying voltages and other events that push the system in unsafe operating regions usually develop slowly – and then, all of a sudden, events precipitate almost instantly and do not leave time to react. It is precisely because of this aspect that one needs to detect as early as possible that the operating conditions are deteriorating towards a state where the blackout is unavoidable. And since the system operating conditions change continuously, quantifying and posting the risk of instability needs to be performed for each new operating state.

In addition, since we also have to prevent approaching states that may be too dangerous, we first need to detect that the system is moving in the wrong direction so there would be enough time to take early corrective action. This is also a continuous process, and consists of monitoring how the stability conditions change in real-time, and then issuing warnings if and when needed.

In the context of system operations, the traditional approach has been to compromise between the depth and, respectively, the speed of the stability calculations. The need to compromise between depth and speed can be compensated if a more sensible approach is deployed which encompasses a balanced mix of:

- Approach A: Practically instantaneous assessment predicated on processing and interpreting PMU data
- Approach B: Rapid, although somehow approximate, real-time stability tools running in tandem with state estimators
- Approach C: Precise, yet time consuming, detailed stability calculations.

Appr. A: Supervision and Analysis of Synchrophasors

A method for stability supervision is applied which achieves a precise monitoring of the power grid with quite low effort. The basic idea is to supply the control center operators with a dynamic real time view into the voltages, currents and phase angles of the electric grid. This enables them to understand quickly the actual stability situation and trend in the system. The approach provides a tremendous breakthrough for control room operators since it allows them for the very first time to experience the dynamic behavior of their power system in real-time. In addition, it provides beyond human monitoring capabilities some automatic alarming of potentially dangerous situations. Monitoring and alarming capabilities are limited to the extent of PMUs installed in the field; recommendations on corrective/preventive actions are not provided.

Appr. B: Real-Time Calculation of the Steady-State Stability Limit

The Steady-State Stability Limit (SSSL) of a power system is "a steady-state operating condition for which the power system is steady-state stable but for which an arbitrarily small change in any of the operating quantities in an unfavorable direction causes the power system to lose stability" [8]. Approaching the search for a "stability limit" from this perspective brings promising results. First and foremost, the SSSL is mathematically definable, can be computed with relative ease, and does represent an operating limit, albeit one that is:

Local, rather than global, i.e., it depends both upon the current state vector and the assumptions made to "worsen" the case, and

Unsafe, in the sense that operating states immediately below this limit may quickly, or even instantly, become unstable.

Then, the SSSL can be quantified, i.e., can be expressed in terms of the total MW loading of the transmission system, including both internal generation and tie-line imports, under a given scenario of bus voltage conditions. On this basis, a metric [4] can be defined to quantify "how far from SSSL" is a given operating state. Known as steady-state stability reserve, this index was introduced in Europe by Paul Dimo [2], [3]. The algorithmic foundation of this technology has been extensively documented [5], [6], [7], [9], and is briefly summarized later in this paper. A visualization of the SSSL concept is given in Figure 1. Please note that just for the sake of easy visualization a simplification was applied by only illustrating the curve of load MW vs. rotor angle for a single-line-single-generator configuration.

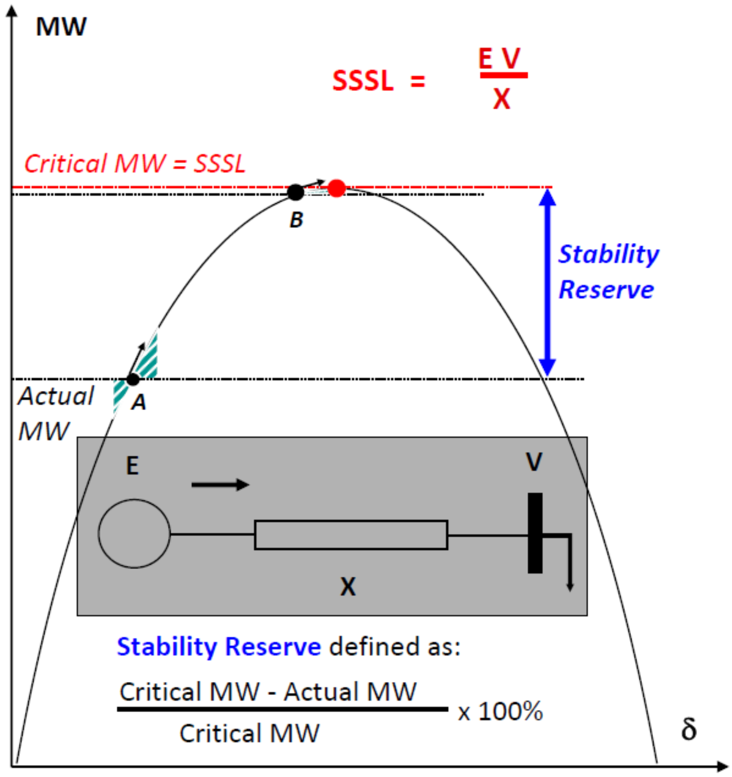

Figure 1: Simplified visualization of the Steady State Stability Limit (SSSL)

Approach B does not depend on particular hardware in the field; it only needs a few pieces of data beyond what is needed anyway for running State Estimators (SE). Approach B allows the computation of a system-wide quantifiable dynamic security index in the SE periodicity; it includes the consideration of contingency cases as well as some capabilities for providing preventive measures in cases of insufficient stability reserve.

Appr. C: Detailed Dynamic Disturbance Simulation and Analysis

To accurately assess the security of a power system, a flexible and modern assessment framework is essential [13]. It should aim to perform the analysis in real time and provide reliable results. Elements of such a framework can be grouped into the main components illustrated in Figure 2.

The accuracy of a Dynamic Security Assessment (DSA) system is strongly related to the quality of input data. Important are a detailed representation of the power system, the interacting protection system, a credible snapshot of the system's state and if available forecasts for renewable energies, loads and the energy trade. The power system will be modeled with all passive equipment (wires, cables, transformers, …) and all active, switched or controlled equipment (generators, capacitor banks, FACTS, HVDC, …) including their controllers.

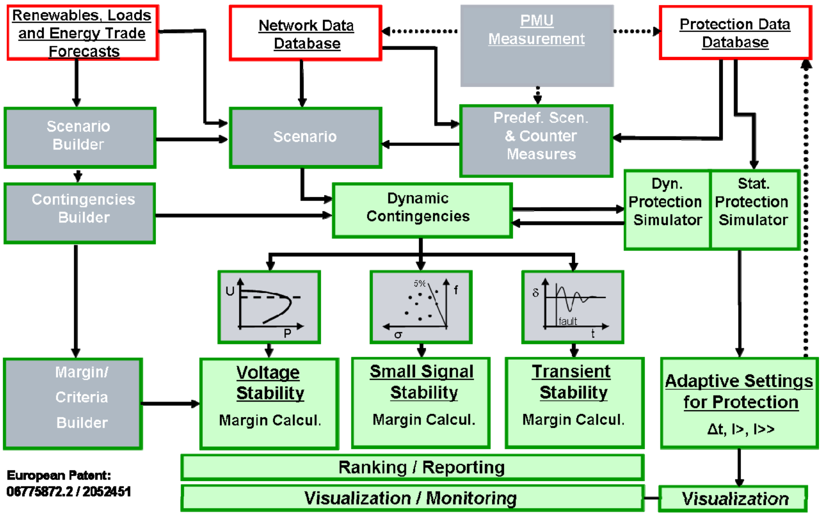

Figure 2: Principal Structure SIGUARD® DSA

A power system has to be operated in accordance with the system load, operational as well as security constraints. The requirements for a DSA are therefore to prove whether the system would fulfill the constraints after outages or severe system faults under different system states. The DSA checks the security criteria like overload, dynamic under-/overvoltage dynamic under- / over- frequency, stability, damping etc. These criteria can be combined individually to define a suitable set of criteria to describe the constraints of the system. A fuzzy logic is used to define security indexes to rank the system state, to reduce the large amount of information to a "signal light" for the state of the overall system stability.

Instantaneous assessment of system stability predicated on processing and interpreting PMU data

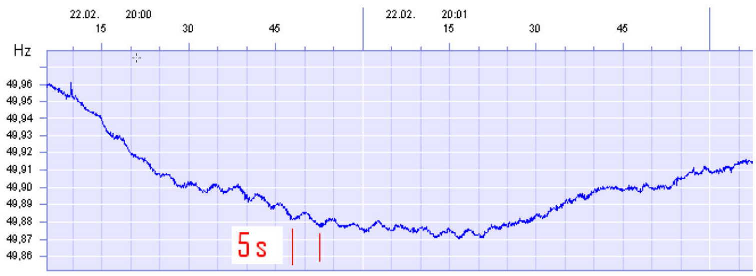

Figure 3: Example for frequency measurement with PMU

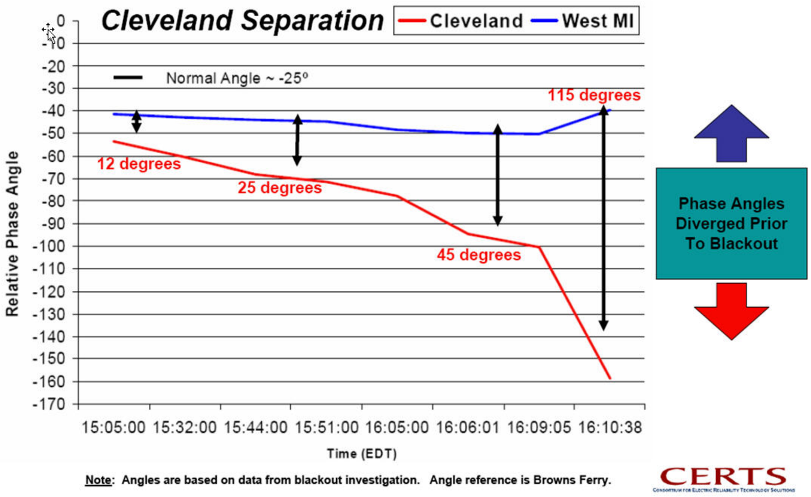

Figure 4: Phase angle during blackout in the US on Aug 14, 2003
(taken from www.naspi.org)

The following applications of synchrophasor measurements can support the system operator in analysis and prediction of system stability:

Frequency Monitoring: Figure 3 shows a frequency measurement by a PMU during a scheduled power plant switching at 8:00 pm in the ENTSO-E network in Europe. The east-west-mode (0,2Hz) can be seen quite well with small amplitude. Such a frequency curve allows checking the existing network model and the known power swing modes.

Phase Angle Monitoring: Phase Angle differences indicate the power flow between two locations in the power grid (see Figure 4). This schematic diagram shows that the upcoming blackout could have been seen in advance if actual phase angle measurements would have been available.

Figure 5 shows phase angle measurements from PMUs during a switching off of coupling lines between two regions. The phase angle of the voltage changes immediately and goes with a well damped oscillation into the new state. These curves show that the system state remains stable. If the phase angle would not go towards a new constant value, the operator would be immediately aware that predefined corrective actions have to be taken.

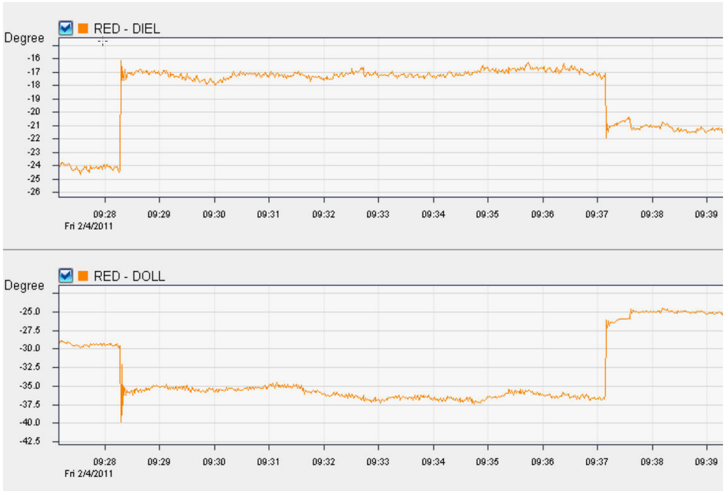

Figure 5: Phase angle on two lines after switch events

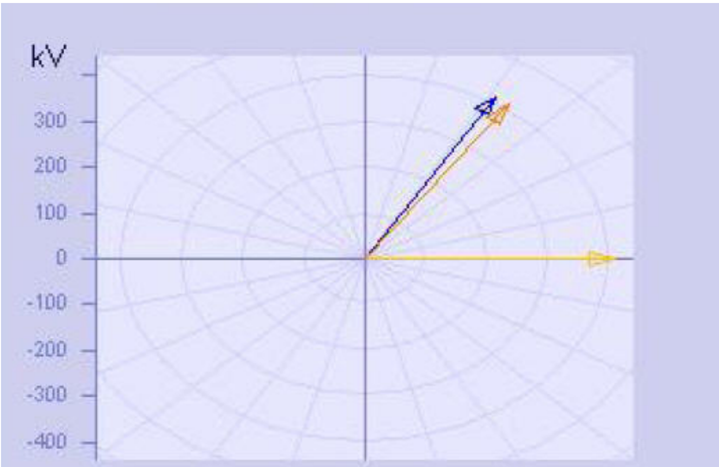

Figure 6: Voltage phasors in two regions – North (blue and orange phasor) and South (yellow phasor)

Voltage Monitoring: An example for voltage monitoring is shown in Figure 6. Two phasors are measured in the northern region and the third is acquired in the south. The actual phase angle of nearly 60 degree is an indicator for strong power flow from the north to the south. The distance to the stability limit (90 degree) can be continuously supervised. Note that no topology information of the network is needed to gain this information.

To support the operator in interpreting the time-synchronized measurements from the PMUs, several applications can be offered in **Wide Area Monitoring** systems:

Power Swing Recognition: The idea of power swing recognition is to analyze selected measurements continuously to detect power swings. The parameters damping, amplitude and frequency (mode) of the power swing determine when an alarm is generated. To support the awareness for the problem, the power swing is displayed in a geographic overview of the system.

Island State Detection: Because every PMU sends a frequency measurement to the Wide Area Monitoring System, it is possible to compare them. If a difference is detected, this is a hint for a system separation which generates an alarm and is also shown on the geographic overview.

Voltage Stability Curve: The Voltage Stability Curve shows the actual operating point of a line on a Voltage-Power-Curve. Two PMUs on both ends of the line supply the application with the actual voltage and currents. With the known impedance of the line, the dynamic difference to the stability limit of the line can be shown.

Real-time stability tools running in tandem with state estimators

Brief algorithmic background

A good example of a real-time steady-state stability assessment tool running in tandem with the state estimator is offered by QuickStab®. In a nutshell, this technology is predicated on the:

- Short-circuit currents network transformation instead of performing computations on the full network model
- Zero Power Balance Network method to aggregate the system loads into a fictitious load-center.

- Representation of generators via internal reactances coupled with an empiric method to detect the MVAr saturation of the machines
- Reactive power steady-state (voltage) stability criterion to detect the singularity of the dynamic Jacobian instead of computing and assessing eigenvalues
- Case worsening procedure for stressing the system conditions instead of performing a sequence of load-flow computations

The **short-circuit currents transformation** is used to convert the power system network, which is highly meshed, to a scheme of short-circuit admittances connected radially to a nodal point. The radial network of short-circuit admittances thus obtained is known as the REI Net. One of the key attributes of this transformation is that it allows "seeing" the generators from the nodal point. The transformation of a meshed power system network to an REI Net can be applied to an actual load bus, to connect it radially with all the generators by means of short-circuit admittances, or to the fictitious load center obtained by first introducing the Zero Power Balance Network as shown below.

Paul Dimo introduced the **Zero Power Balance Network** for the purpose of aggregating the system loads into a fictitious single load-center while preserving the properties and the power balance of the base case. This method is known in the industry as "REI equivalencing" and has been demonstrated to be accurate if the individual bus loads vary conformingly with the total system load. It must be emphasized that in the context of evaluating stability, the machines, either real, such as generators and synchronous condensers, or "virtual", such as tie-line injections, are not equivalized and the Zero Power Balance Network is used only for the purpose of building the fictitious load center. If the short-circuit currents transformation is applied after having introduced the Zero Power Balance Network, the REI Net thus obtained will connect the system generators to the fictitious load center, rather than to an actual load bus.

During the electromechanical oscillations, typically between 0.3 and 2.5 Hz, that take place after a small perturbation that causes a machine to change its MW output and to settle in a new stable state, the generator appears to have an internal reactance smaller than the steady state reactance - this is the transient reactance x_d'. Accordingly, the "classic" **generator model** consists of representing the machine as seen from the stator as a constant emf E_d' behind the transient reactance x_d'. This model is very attractive due to its simplicity. A further enhancement consists of reverting the generator's model to x_d if a state where both P_{max} and Q_{max} limits of the generator is reached. The theoretical justification of this approach is documented in the Appendix A of reference [7].

Using the reactive power steady-state (voltage) stability criterion $d\Delta Q/dV$ to detect the **singularity of the dynamic Jacobian** instead of computing and assessing eigenvalues is made possible by the radial nature of the REI Net that connects the machines to a central node. On this basis, the point of instability is identified by simply evaluating a trivial algebraic expression [2], [3], [5], which is where the extraordinary speed of the QuickStab technology is coming from.

Finally, the **case worsening procedure** to quantify the distance to instability allows stressing the system until it becomes unstable without having to recompute load-flows. In voltage and steady-state stability problems it is not the base case, which presumably comes from a fully converged load-flow or state estimate, that is of primary importance, since, in most cases, the base case is stable. What really counts is the ability to characterize the system state by its "distance" from an unstable one. The stability calculations per se, either via simplified techniques such as practical stability criteria, or based on detailed simulation, e.g., evaluating the eigenvalues of the Jacobian associated with the system of dynamic equations, do not give such information. In order to identify the Steady-State Stability Limit (SSSL) and, implicitly, to find the distance to instability, the calculation of the steady-state stability criterion must be combined with a system stressing procedure whereby various system parameters are changed in a direction that is unfavorable to stability. This is achieved by the case worsening procedure which is used, instead of a succession of load-flow computations, to stress the system until it becomes unstable. Throughout the case worsening process the system model remains constant. If major topology or other changes need to be simulated, e.g. line and generator contingencies, a new load-flow solution needs to be computed as well. Once the base case has been recalculated, the REI Net and the Nodal Image are updated, the case worsening procedure is performed, and the SSSL, steady-state stability reserve and security margin for the new system state are obtained.

The SSSL thus calculated tends to be conservative at low system loadings, but the prediction of the distance to instability becomes more accurate when the total MW system loading increases and additional reactive compensation resources get committed. This apparent paradox can be explained if we note that operating policies typically call for raising TCUL taps, removing shunt reactors, adding shunt capacitors and bringing online synchronous condensers when the system is approaching peak-load conditions. At medium and light load levels, capacitors are removed, shunt reactors are reconnected and synchronous condensers and/or units that were running essentially for generating MVArs are taken off-line. The net result of such operating procedures is that the network's maximum loadability gets pushed at values that could be much higher than those at medium and light load levels.

Integration with SCADA/EMS

As emphasized above it is of crucial importance that the system stability indices such as the distance to SSSL are continuously updated for the operator i.e. its computation and visualization must be closely integrated with the SCADA/EMS of the transmission grid company. In this effort it is important there is …

- immediate update of the operator on the distance from instability periodically as well as after each significant system change e.g. CB tripping
- display of the decisive results in the user interface of the SCADA/EMS, particularly the trend curve of the 'distance to SSSL'
- capability to evaluate system instability for perceived situations by means of the familiar SCADA/EMS study case management and in the same convenient way as in real-time.

The simplest way to integrate QuickStab with a SCADA/EMS is to install it on a separate PC connected to the SCADA/EMS LAN. On the SCADA/EMS side, after each successful execution of the SE, the output is saved in PSS/E format. On the PC side, a control program runs at fixed time intervals that are user definable, e.g., 5, 10, 15, etc. minutes. The control program retrieves the most recent state estimate file from the SCADA/EMS server, copies it on the PC, and then automatically triggers the QuickStab computational engine. Upon completion of the stability calculations, the control program triggers the display engine of QuickStab to present the results on the PC. This integration approach is very simple to achieve since it does not mean any adaptations to the SCADA/EMS provided that the SCADA/EMS can generate a PSS/E formatted output file [9], [10]. However, it does not fulfill all the requirements above. A more advanced stage of integration [1], [6], [9], [10] is achieved by including some adaptation to the SCADA/EMS: after each successful execution of SE or Dispatcher Power Flow (DPF), the output is saved in PSS/E format on the PC; then, a QuickStab control module on the PC is activated which triggers the sequence of stability calculations both for the base case and for a predefined list of single and /or multiple contingency cases. If so desired, this control module also launches the QuickStab display engine which presents the results in graphical format. When the PC process has completed, the SCADA/EMS control program retrieves the results and saves them in the SCADA/EMS real-time database. Compared to the basic, loosely integrated solution, the essential achievements of this more advanced approach are (1) triggering the QuickStab calculation with **each** SE activation (i.e. including spontaneous ones) and with each DPF activation, and (2) writing key results into the SCADA/EMS **real-time database** which, in turn, makes it possible to display them with any displaying tool available in the particular SCADA/EMS as well as to archive them. The latter feeds the key display the control room operator will usually watch closely: the trend curve of the distance to instability, a simple yet extremely important tool with the capability to provide early warnings when the power system approaches instability. The fact that QuickStab simply shares the contingency lists available in the Network Analysis subsystem of the SCADA/EMS further increases the acceptance of the QuickStab tool by the control room user.

The final stage of **seamlessly** incorporating QuickStab into the SCADA/EMS platform was recently reached by integrating the QuickStab software completely with the Network Analysis package of the SCADA/EMS. This eliminates the need for a dedicated PC and makes the real-time calculation of the distance to instability a regular part of the SCADA/EMS functionality. In this role QuickStab does not significantly add to the run time of its SE tandem partner: QuickStab solves, for instance, 2,000 – 3,000 bus systems in less than a second – on regular laptop computers.

Precise and detailed stability calculations

Dynamic Security Assessment with SIGUARD® DSA

Network disturbances such as short-circuits, equipment and generator failures as well as sudden network changes, caused by switching, create electro-mechanical transients [16, 17]. Whether these events do not only endanger the steady-state but also the transient stability is analyzed beforehand. In order to consider the influences and limits caused by the protection system, e.g. in case of overload or power oscillations, the dynamic simulation software is able to simulate the protection devices of many different manufacturers including all their characteristics and communications. Also out-of-step protection relays and vector-jump relays are considered. This is indispensable as the relays have direct impact on the switching condition of the network through the circuit breakers they are assigned to. That is the only way, the danger of cascading outages, as occurred at beginning blackouts, can be identified. The DSA system is able to not only assess the dynamic state of the system, but also to determine, rate and visualize the margins to critical states of the system [15]. To do so, an interconnection to existing control systems is essential, in order to provide continuous snapshots of the actual, quasi-steady-state condition of the system as a basis for the dynamic security assessment [18].

If network outages are simulated and possible dynamically critical conditions are found, the DSA system finds measures and solutions that will keep the system or bring it back in a stable and secure mode. Some examples for such measures are blocking of transformer tap changers (OLTCs), switching of available reactive power components, islanding, load shedding, or generation shedding.

SIGUARD DSA uses the simulation software PSS®Netomac [14] as core engine. With PSS®Netomac it is possible to carry out the dynamic outage simulation faster than in real-time using a standard PC. As computation engine, PC clusters can be used to run Netomac on large numbers of cores in parallel.

Brief algorithmic background

SIGUARD DSA is running voltage, small-signal and transient stability analysis in parallel as well as the check of grid code constraints (see Figure 7). All the simulations end up in standardized indices, which will be combined by a fuzzification system acc. to Figure 8 to a stability "signal light" of the actual stability state of the power system or also acc. to Figure 8 to a "signal light area" where the stability impact of all contingencies for all chosen future working points is visualized for the operator's information.

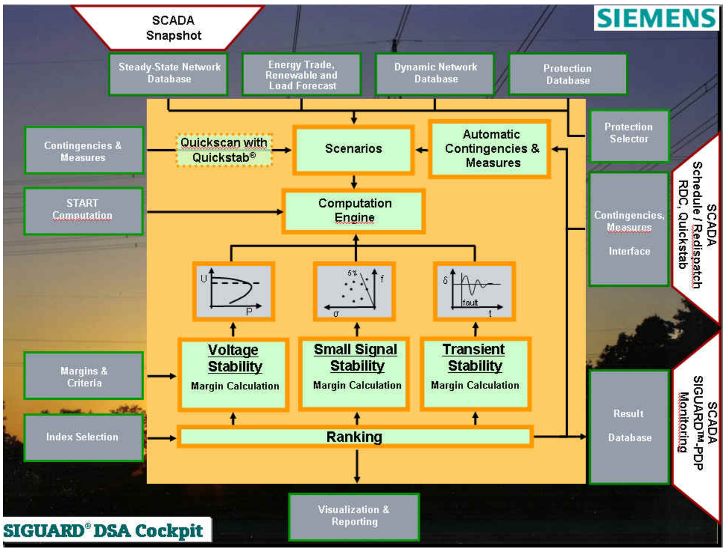

Figure 7: SIGUARD DSA Cockpit with internal real-time application (orange) and external user applications.

Project application

At the exemplary project for a nationwide transmission network in North Africa [19], [20], where SIGUARD DSA is already in use, it could be shown, that in the time between two consecutive snapshots of the State Estimator (15 min) more than 2,000 dynamic transient stability simulations with a time step of 20ms are possible using a cluster of only 10 PCs. This means that the outage of all equipment of the transmission network could be simulated, if wanted, and the dynamic stability of the network can be assessed.

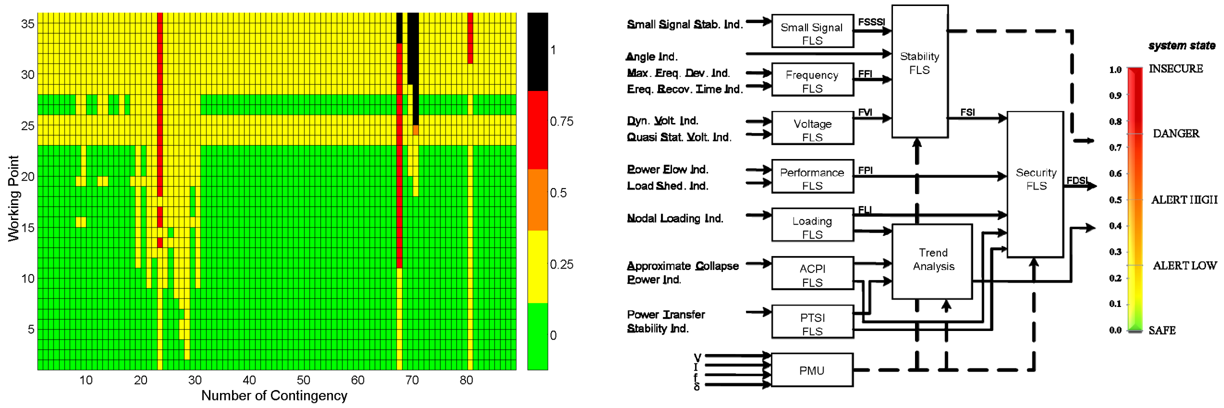

Figure 8: Stability fuzzification system with "signal light" and stability "signal light area" for a (N-1) line- outage simulation and 35 future system states.

Analyses of past blackouts showed, that there is always a time period of 20 - 30 minutes between the first critical network outage and the following cascading disconnections. The typical snapshot time step of 15 minutes or less is therefore completely sufficient to identify critical network conditions, to propose countermeasures and therefore to prevent blackouts.

Outlook

As of today, the three approaches to the detection and mitigation of the risk of blackout described above are more or less independent tools. However, the control room user will gain additional benefit from their interaction. Therefore it is planned to develop interfaces between the tools according to Figure 9.

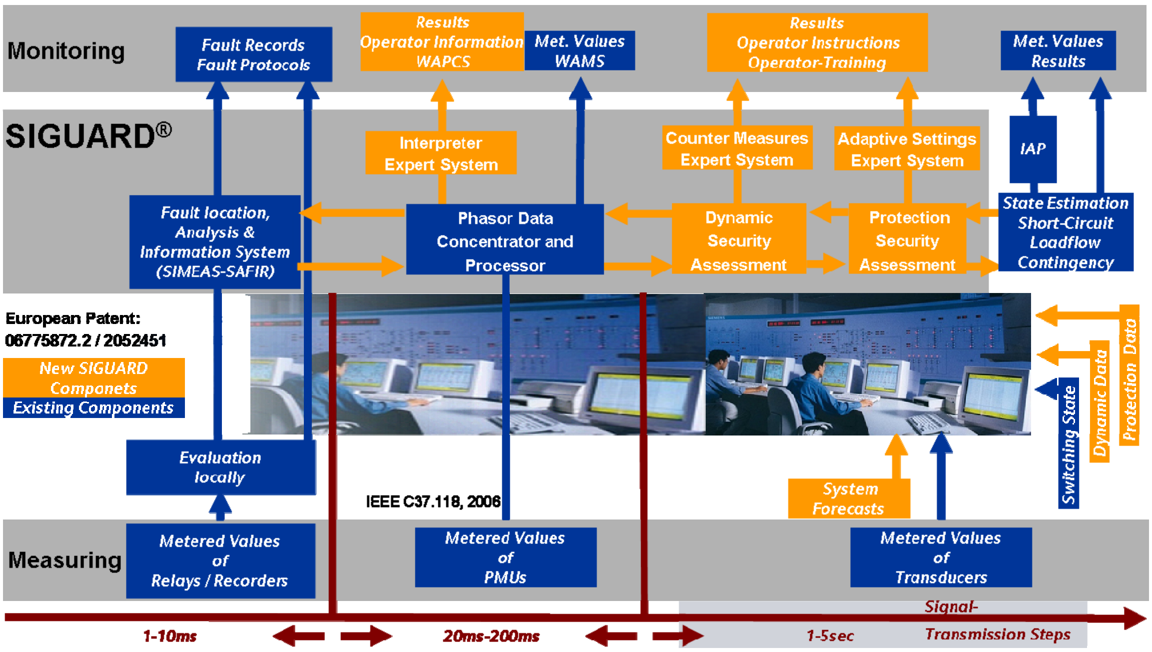

Figure 9 : Overview of SIGUARD integrated tools for Blackout Prevention

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