21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

Risk Assessment and Operational Security
253

LISBON 2013

Visualizing the risk of blackout in smart transmission grids

B. O. STOTTOK SIEMENS AG Germany

Dr. C. O. HEYDE SIEMENS AG Germany

Dr. R. EICHLER SIEMENS AG Germany

Dr. S. C. SAVULESCU Energy Consulting International, Inc. USA

SUMMARY

Under today's operating conditions with increased uncertainty of the patterns and directions of the power flows in the transmission grids, unplanned transmission outages and deteriorating voltage conditions will push the power system towards states where voltages may collapse and units may lose synchronism. The inherent difficulty of handling such deteriorating states stems from the fact that blackouts do not happen suddenly out of the blue – they develop slowly and, when the system is "ripe for blackout", events precipitate almost instantly and do not leave time to react. Therefore, in order to *prevent* a blackout, one has to *predict* it, i.e., to *detect* that the system is moving towards the wrong direction, which, in turn, requires fast computations to allow *monitoring* the system's stability conditions in real-time.

This paper tackles the difficult problem of presenting timely, efficiently, and effectively the relevant information that can help a power system operator detect and prevent the risk of blackout due to instability. This is particularly critical in the context of modern control centers where the large amounts of raw data and calculation results generated by *computers* need to be absorbed, filtered, and mentally processed by *humans* – quickly, reliably, and within the short time span required to make online decisions in system operations. To further compound this already significant difficulty, stability computations are extremely complex and produce results that are not necessarily easy to interpret and understand.

The paper identifies numerical indicators that encapsulate information which can help determine the: *instant status* of the degree of operating reliability, or security margin, of the power system at any given point in time; and the *trend* of the system conditions either towards or receding from the hypothetical state where the blackout may be unavoidable. These information visualization methods are extensively illustrated with screenshots from existing control centre tools.

KEYWORDS

Smart Grid - SCADA EMS - Transmission - Blackout Prevention - Stability - Visualization - Trend

bernd.stottok@siemens.com

1. Status Quo

The increase of consumption of electric energy during the last decades has led to an expansion of synchronously operated AC systems as well as to higher voltage levels. All around the world, technical and economical advantages of combined operation have caused the interconnection of adjoining grids. With a view to development of environmental impacts, like the fear of global warming, and the consequently needed reduction of CO_2-emissions, there will be a significant change in used resources and the energy mix. As in the past transmission and distribution network structures were developed in accordance with generation and load structures, structural and operational changes will have to be applied [1] to move towards the smart grid of the future.

Blackouts do not happen out of the blue and without prior signals of distress. Unplanned transmission outages, decaying voltages, and other events that push a power system towards an unsafe modus operandi usually develop slowly, but then, within milliseconds, events occur almost instantly and do not leave time for the operator to react. This is the reason why one needs to detect as early as possible when the operating conditions of the power system are developing towards a state where a blackout will become unavoidable. And as the operating conditions change continuously, quantifying and posting the risk of instability needs to be performed for every new operating state [2].

Blackouts and large-area outages in America and Europe have confirmed that the interconnection of adjoining networks is beneficial in terms of operation and economy; however, this also bears the risk of uncontrollable, cascading outages [1]. Especially when grids are operated close to their thermal limits in certain areas, stability and protection problems will occur [3]. To have enough time to take early corrective actions and to prevent approaching states that may be too dangerous, one first needs to detect that the power system is moving in the wrong direction at all. This is also a continuous process which consists of monitoring how the stability conditions change in real-time and then issuing warnings if and when necessary [2].

2. Basic Concepts of Detection and Quantification of the Risk of Blackout

An important goal of dynamic security assessments is to determine if a power system is able to withstand a series of major contingencies. Another important goal is to evaluate the risk of possible instability if the power system tumbles slowly towards a dangerous state, which could be the result of either a small topology and/or load changes together with slow bus voltage changes that might trigger a voltage collapse, and/or slow load increases which might finally cause one or several generators to lose synchronism. Instability in a power system can also be caused when attempting to transfer large MW blocks to compensate load increases and/or generation outages in certain areas of the power system, thus increasing generation somewhere else. Instability also will take place when units lose synchronism because of self-oscillations [2].

In today's control room environment there are basically three approaches that in some respect complement each other and help the operator to mitigate the risk of blackouts successfully. All of them support the operator in monitoring how the stability conditions change in real-time and then issue warnings if and when needed.

(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 on the control centre side. The basic idea is to supply the control centre operators with a dynamic real time view into the voltages, currents and phase angles of the electric grid by **Phasor Data Processing (PDP)** system. This enables them to understand quickly the actual stability situation and trend in the system [2].

However, to observe that a blackout is approaching solely from Phasor Measurement Units (PMU) data either requires an immense level of expertise or support with additional information.

(B) Real-time calculation of the Steady State Stability Limit: Another approach is to run rapid, although somehow approximate real-time stability tools with input from the state estimator, i.e. to quickly calculate the power system stability **(QuickStab)**.

A stability index for power system stability monitoring in real-time which is well-suited and field-proven is the Steady State Stability Limit (SSSL) [4]. The 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" [5]. The SSSL is mathematically definable, it can be computed, and it represents an operating limit, albeit one that is local, rather than global, and which is unsafe in the sense that operating states even just below this limit may become quickly, or even instantly, unstable. In addition, the SSSL can be quantified in terms of the total MW loading of the transmission system, considering both internal generation and tie-line imports [2]. Based on this, a metric [6] can be defined to quantify "how far from SSSL" is a given power system operating state [2].

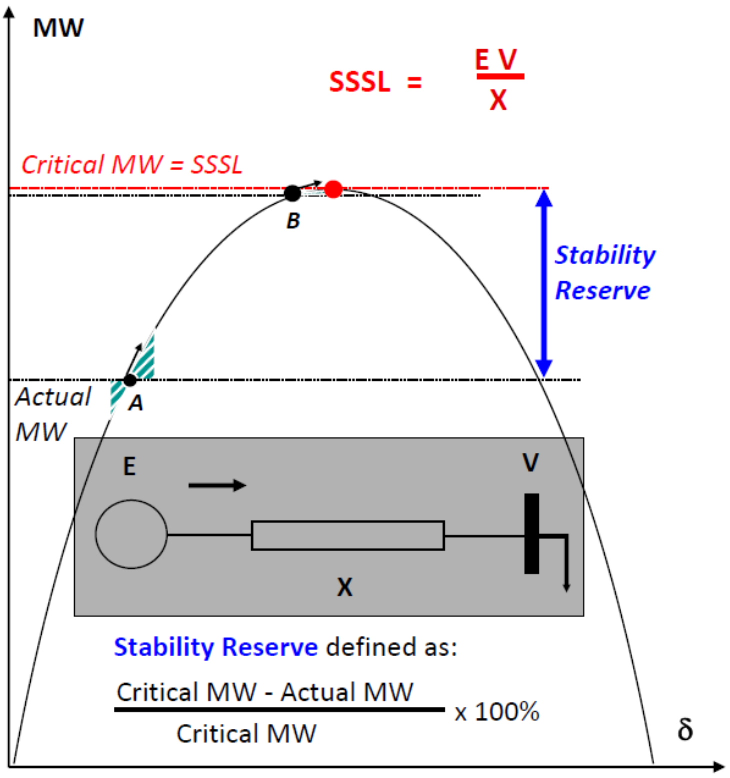

Figure 1: Simplified visualization of the Steady State Stability Limit (SSSL)

A visualization of the SSSL concept is given in Figure 1. Please note that for easy visualization reasons a simplification was adapted, only illustrating the curve of load MW vs. rotor angle for a single-line-single-generator configuration [2]. This solution does not depend on particular hardware in the field, as it only needs a few pieces of data beyond what is needed anyway for running State Estimators (SE). This approach allows the computation of a quantifiable, power system-wide dynamic security index in the SE periodicity. And it also includes the consideration of contingency cases as well as some capabilities for proposing preventive measures in cases of insufficient stability reserve [2].

(C) Detailed dynamic disturbance simulation and analysis: Another proper solution to detect that the power system is moving in the wrong direction is to do precise, however time consuming, detailed stability calculations, i.e. to perform **Dynamic Security Assessment (DSA)** [2]. To assess the security of a power system in an accurate manner, a flexible and modern assessment framework is needed [3], aiming at to perform the analysis in real-time and to provide reliable results [1]. Elements of such a framework can be grouped into the main components illustrated in Figure 2.

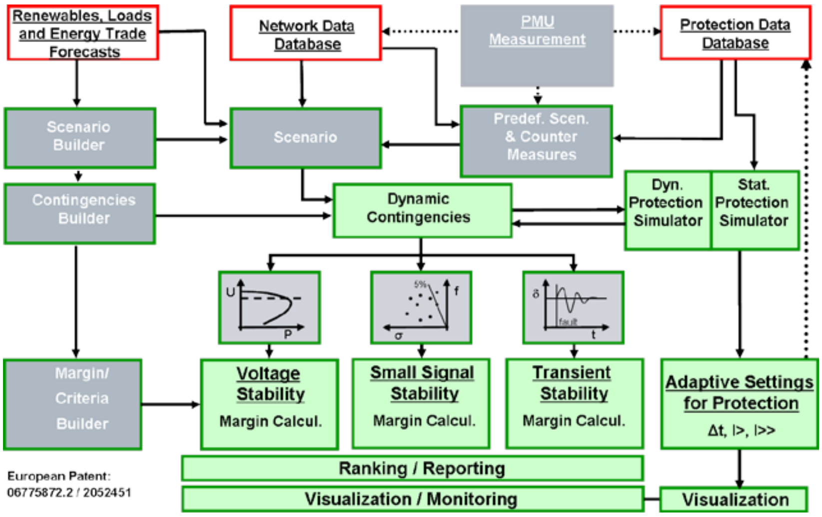

Figure 2: Principal structure of SIGUARD® DSA

Network disturbances, e.g. short circuits, or network changes create electro-mechanical transients. Such events threaten the steady state and even more the transient stability of a power system [7], [8]. DSA allows analysing the current and future dynamic of an electrical system [9]. Moreover, with a proper DSA system it is possible to simulate and verify preventive, corrective, and emergency actions before they are actually enacted by the operator.

The accuracy of a DSA system is strongly related to the quality of the input data. Important are a detailed representation of the power system, the interacting protection system, a reliable state estimate, and, if available, forecasts for renewable energies, loads, and the energy trade. The power system will be modeled including all passive equipment (wires, cables, transformers, …) and all active, switched, or controlled equipment (generators, capacitor banks, FACTS, HVDC, …) plus their controllers [2].

The DSA checks the time domain simulation results against stability constraints like damping, dynamic voltages/frequencies and rotor angles, and operational constraints like loading, fault ride through and so forth. These criteria can be combined individually to define a suitable set of criteria to describe the constraints of the power system. Fuzzy logic is used to define security indexes to rank the system state, thus reducing the huge amount of information to a “signal light” for the state of the overall system stability [2].

3. Visualizing instant status and trend of power system stability conditions

3.1. Visualization based on Phasor Data Processing (PDP)

The User Interface (UI) consists of different components that provide operators with the ability to quickly identify and analyse areas of criticality in the power system:

The **charts window** displays time series (Figure 3) and vector diagrams (Figure 4) of individually measured values or calculated values over a specified time period. Such charts are created by dragging and dropping elements from the PMU measurements list.

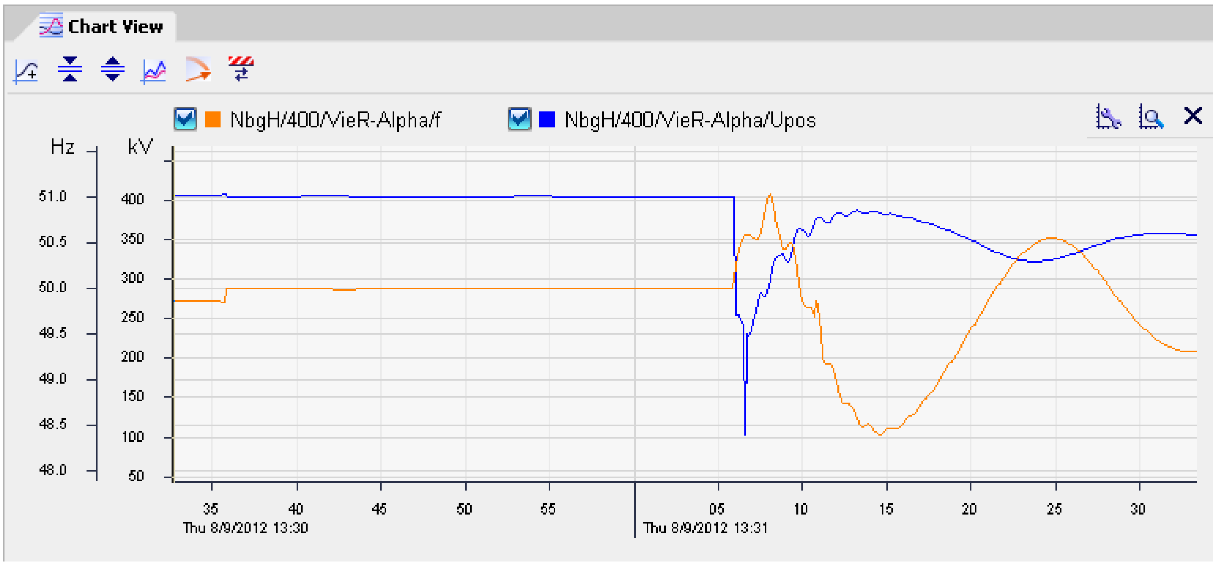

Figure 3: Chart View – Display mode of several curves of a time range

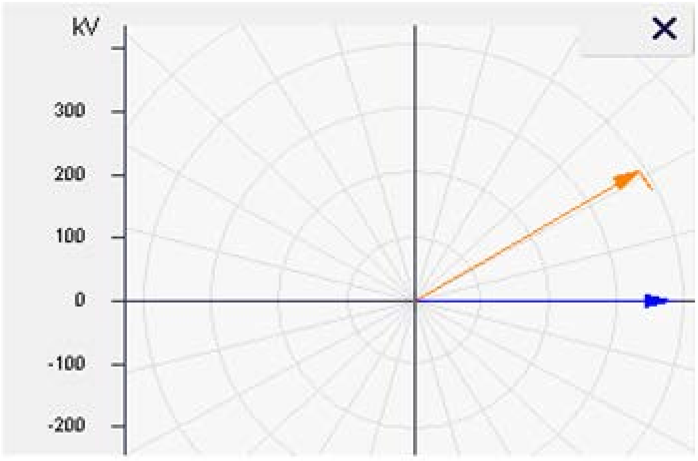

Figure 4: Chart View – Vector diagram of two bus voltages

The **map window (**Figure 5) shows the network topology of the power supply system. Substation symbols and transmission lines are colour coded to show whether those objects are in a normal or critical power state. Objects that are coloured blue are normal, yellow objects are approaching a critical state, and red objects are in a critical state. A swing detected in the electrical power system is shown in the schematic diagram as coloured circular areas around the substations. The circular areas can also be connected by coloured, rectangular areas, if the swing affects several substations.

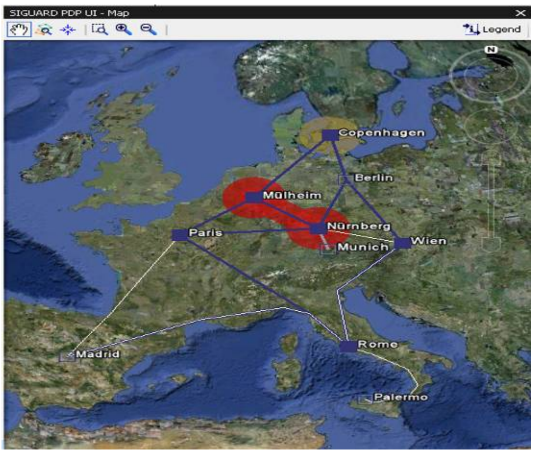

Figure 5: Map based visualization

Another display especially designed for fast reading is shown in Figure 6. Using drag and drop from the power swing analysis list, this diagram can be displayed in the Chart View window section. The diagram shows all recognised power swings for the current time point as dots in the frequency damping diagram. The colours of the dots visualise the criticality of the swings (red = critical, yellow = dangerous) and are defined from their damping as well as from the amplitudes of the swings. The dotted lines represent a damping ratio of 3% or 5%, respectively.

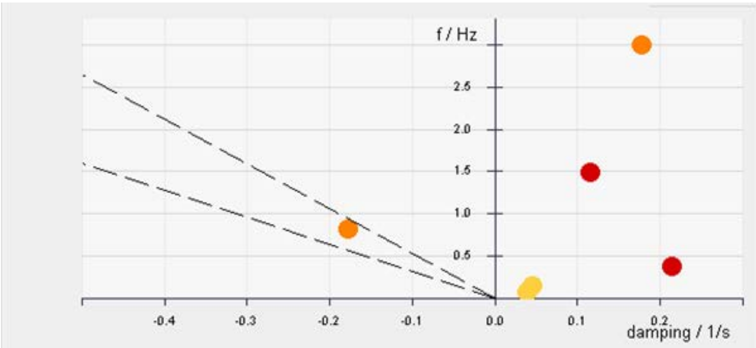

Figure 6: Recognised power swings diagram overview of PMU data or power swings (Frequency over damping)

Visualizing the trend of the power system stability conditions based on a PDP approach looks as shown in Figure 7. A so-called Power System Status curve is calculated from all available measured values for which the limiting values are defined. The user can specify which measured values are to be included in the calculation. The curve is calculated from the weighted distances between the measured values and their limiting values. Critical values of the power supply system are displayed as a red curve in the part of the display above the dotted middle line. The higher the value is represented on the y axis, the more critical it is. In addition, the critical time range is highlighted in light red. Thus the Power System Status window provides a single Go / No-Go indication of system health and criticality for both real-time and past, e.g. for the last two hours.

Figure 7: Power System Status trend curve display of PDP

3.2. Visualization based on Quick Stability Analysis (QuickStab)

One of the key displays that are continuously updated on an operator console is the so-called Two-Speedometer Chart for the base case, i.e. the current system state as computed during the most recent successful run of the state estimator (see Figure 8). The left hand speedometer displays the distance to instability on a linear MW scale. The needle corresponds to the total MW system grid utilisation in the base (current) state. The left edge of the read sector depicts the SSSL. The distance between the black needle (base case) and the red area (critical state) is quantified by the stability reserve in [%] below the SSSL. The width of the yellow sector is proportional with the percent value of the security margin. This representation can be related with the "stability envelope" concept illustrated in Figure 1, where the "safe" operating region is shown in green and corresponds to total system MW loadings smaller than the MW security margin.

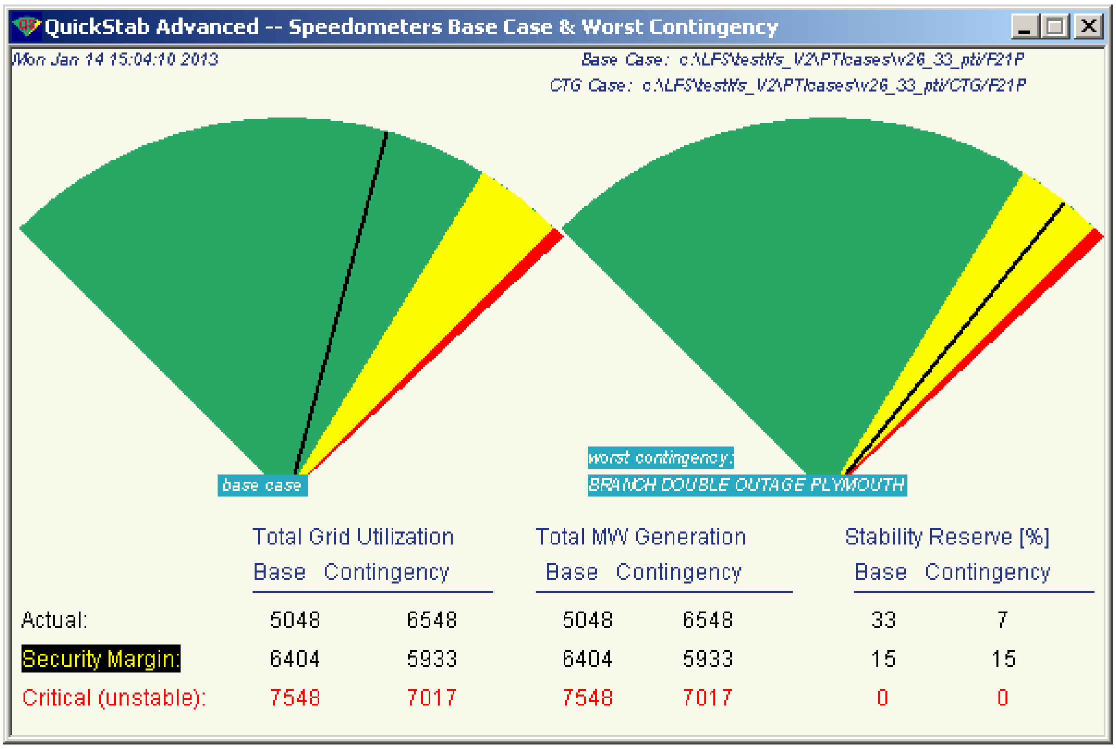

Figure 8: QuickStab Two-Speedometer Chart depicting the distance to instability (red) and to the security margin (yellow)

The right hand speedometer shows the distance to instability not for the base case but for the worst contingency simulated. In the example shown above, the worst contingency would reduce the stability reserve from 33% in the base case down to 7% and thus drive the system right into the middle of the yellow area. This indicates to the operator that the power system is severely at risk once this double branch outage should occur.

Generally, it is of crucial importance that the system stability indices, e.g. the distance to SSSL, are continuously updated for the operator. Therefore their computation and visualization must be connected to the SCADA/EMS of the transmission grid control centre. In order to efficiently support the operator monitoring and controlling a transmission grid while facing rapid loading and generation pattern changes, it is important there are [2]:

- immediate information for the operator on the distance from instability, periodically as well as after each significant system change, e.g. a circuit breaker tripping;
- display of the decisive results in the UI of the SCADA/EMS, especially the trend curve of the "distance to SSSL";
- capability to evaluate system instability for perceived situations via the familiar SCADA/EMS study case management and in the same convenient way as in real-time.

The trend of the Stability Reserve is the main display of the SCADA/EMS watched by the control room operator for monitoring the power system stability. Figure 9 shows an example from the Transmission System Operator of Bosnia-Herzegovina. The 24 hours curve shows significant changes due to some outages occurring that day; however, phases of decreasing reserve, recovery at as lower level, and again increasing reserves become visible. The current value of the Stability Reserve is also shown at a prominent location in the always visible Basic Signalling Display, as highlighted in Figure 9. Other SCADA/EMS displays showing QuickStab results include a list of generators sorted according to their influence on the Stability Reserve. This list identifies those generators where generation has to be increased (or decreased) in order to enlarge the Stability Reserve.

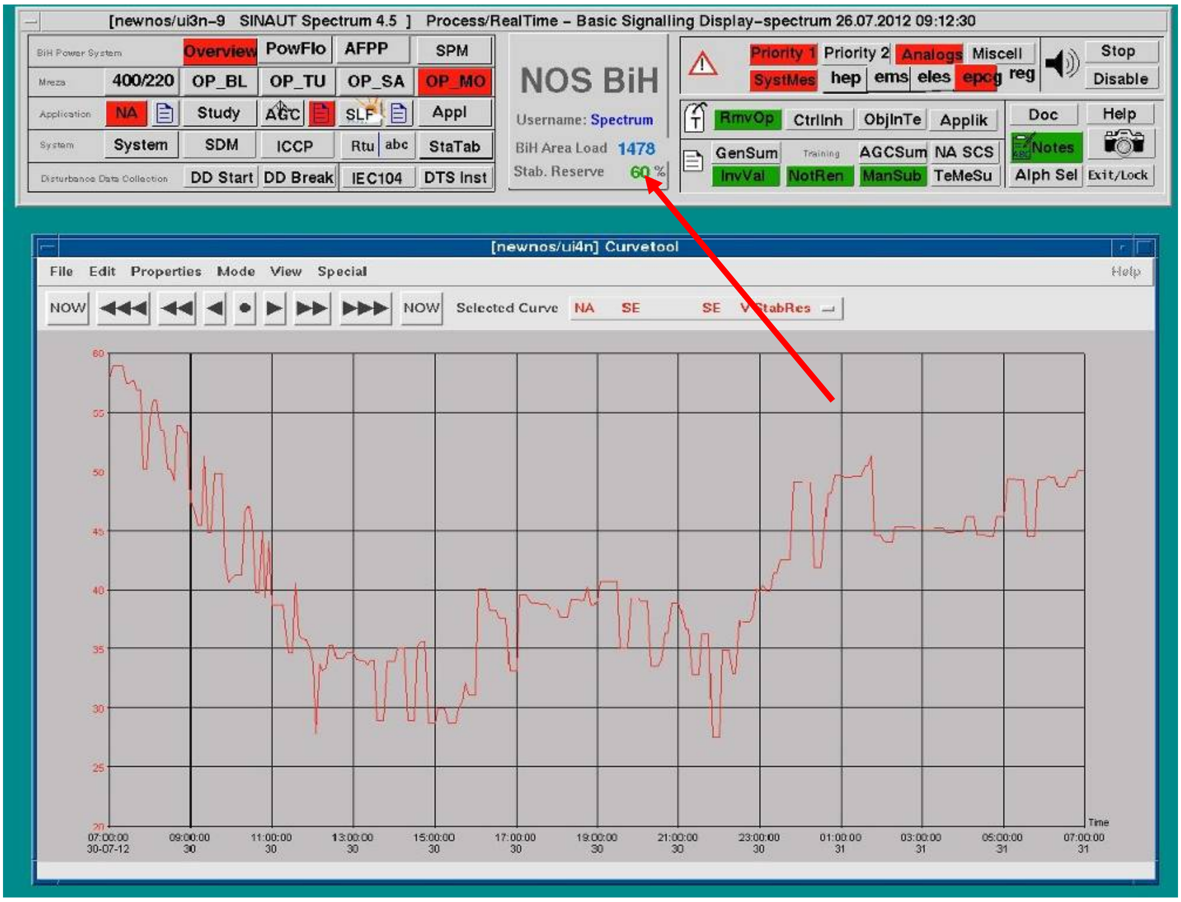

Figure 9: Trend curve of the Stability Reserve integrated in a SCADA/EMS UI

3.3. Visualization based on Dynamic Security Assessment (DSA)

The visualization of the results of dynamic security assessment is realised in several levels of details. The very first display should continuously show the risk of blackout in a traffic light fashion to the control centre staff. Such a first display is shown in Figure 10.

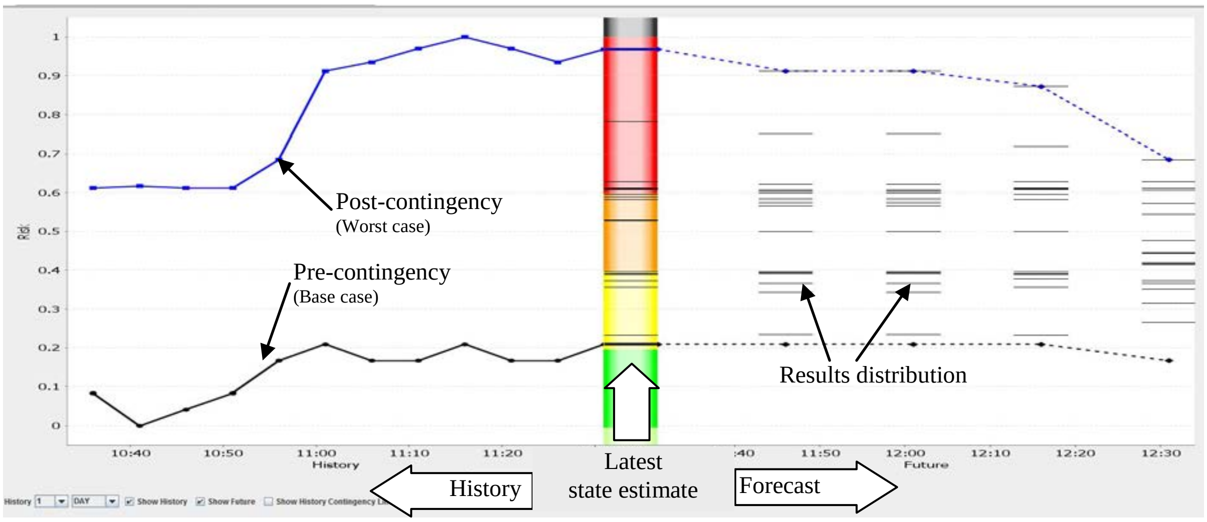

Figure 10: DSA cockpit and first layer of details

The diagram in Figure 10 shows two curves (black and blue). The x axis represents time in the sense of the time during which the state estimator exports the snapshot or the time of the forecast. The y axis represents the risk of a blackout or large disturbance. This risk is scaled between zero and one, where one means high risk and zero means low risk. The black curve indicates the state of the overall power system with respect to stability limits without applying any faults or contingencies (= base case). The risk for this pre-contingency curve is determined from the state estimate based load flow. Alternatively, this value can also be derived from the evaluation of PMU measurements.

The historic results are shown on the left side of the diagram and the forecasts, if available, are shown on the right side. Historic and forecasted results are shown in order to be able to observe the trends of the system. The coloured bar in the middle of the diagram represents the results based on the last imported snapshot from the state estimator. The colouring is customisable and reflects the level of alarm. In this case, black means that system instability would actually occur in case the contingency happens. When the index value is close to one, the system is also close to instability. The result of every single contingency case simulation is shown as thin black line inside the coloured bar representing its severity given by the linear scale of the y axis. With showing these lines, the user is able to see the results distribution and whether there is only one critical contingency or many. In every DSA calculation the topmost black line represents the ranking of the worst case of a large number (hundreds to thousands) of contingency simulations. The blue line connects these particular rankings achieved from DSA calculations done in the past, for the current power system state as well for forecasted ones.

The main messages from the first layer of visualization are as follows:

- What is the current risk of a blackout?
- Do the historic or forecasted results show a threatening trend?
- Is my pre-contingency condition already problematic?
- If a high risk of blackout is indicated, how many contingencies are involved?

In the case of a high risk of blackout the user must be able to investigate the cause and find possible actions to mitigate the risk. Therefore, more detailed information must be displayed subsequently.

Figure 11 shows the results of all contingencies in a ranked fashion. The contingencies are shown in columns. The first column represents the actual state estimate for the selected point in time, whereas the following columns represent the forecasts belonging to this snapshot (the four points in the forecast area of Figure 10). The user can easily find out which contingencies have caused stability problems. The most severe cases are shown on the top of the list. This layer is also used as an access point to the results of each single contingency simulation. At this point, depending on the user's experience, the user can either consult more experienced colleagues or investigate the root cause of stability problems himself. For consulting experts, the system must be designed for multi-users on client server architecture.

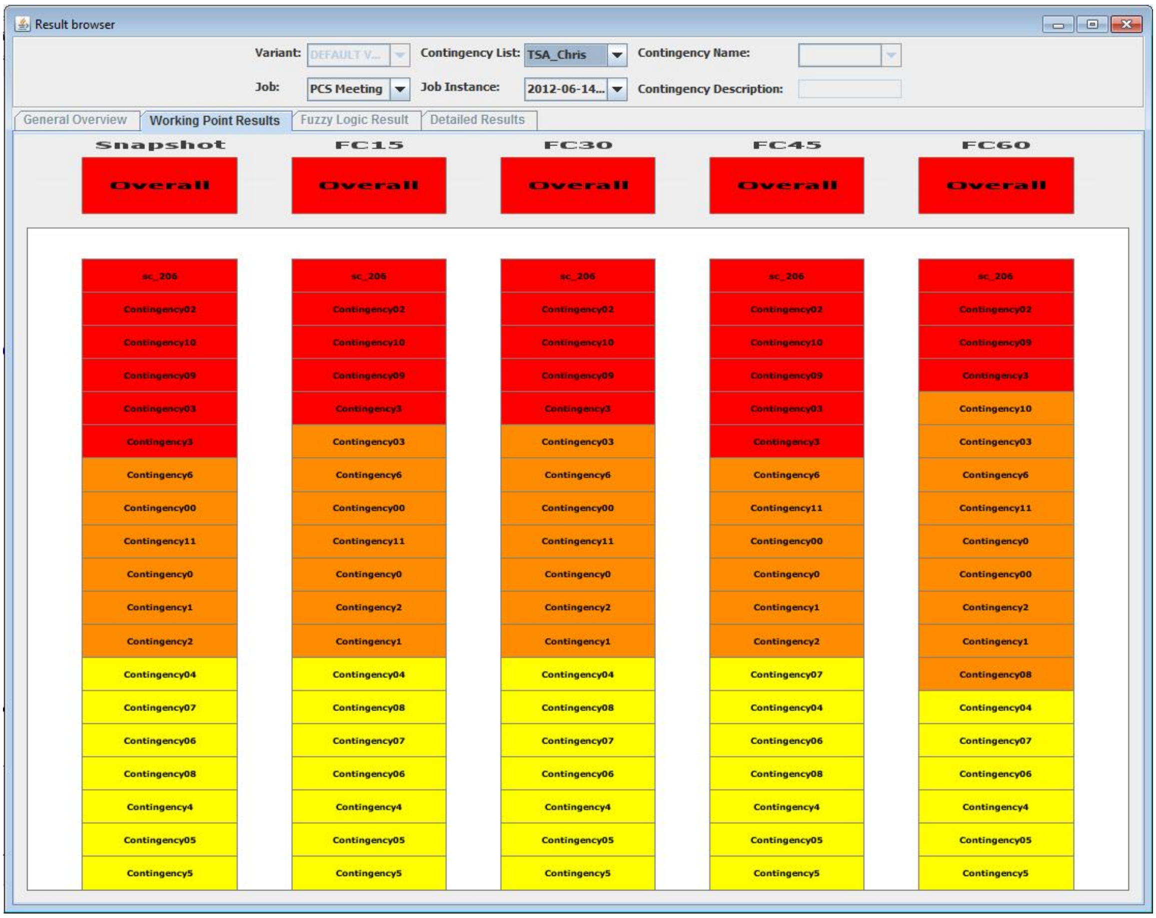

Figure 11: Second layer of DSA results visualization

Figure 12 represents the philosophy of aggregation the huge amount of simulation results to the single stability index. The philosophy is based on a set of indices, each being related to certain phenomena of instability or insecurity of power systems. Some indices are determined element-wise and some are system wide indices. The indices are explained in more details in [10] and [11]. Given these indices, their aggregation is done in a multi-layer fuzzy logic until there is one single index per contingency. Hence, the user sees only the final index on the right side of Figure 12. In order to find out the root cause of the problem, the user can go back from the right side to the left side against the direction of the arrows. Following the worst values, the user can easily find the root cause for the stability risk.

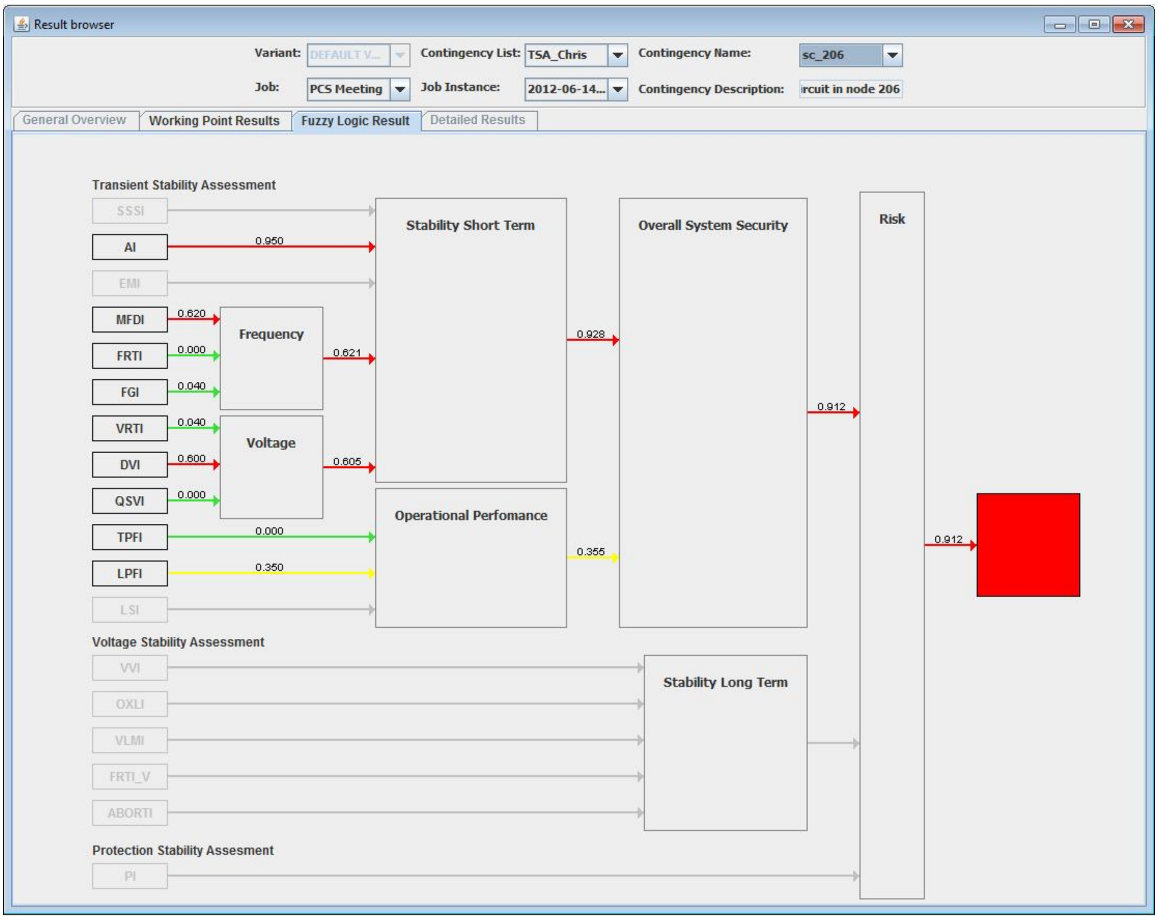

Figure 12: Third layer of DSA results visualization

For further more detailed investigations, the user enters the fourth layer of DSA results representation as shown in Figure 13. In this layer, the user can investigate time curves and single element indices. Knowing the indices for each element and knowing the inception time of these indices enables the user to find out the problematic region and the chronology of security problems. For example, to find proper measures it is important to know whether the low voltage was caused by un-synchronism of a generator or the un-synchronism was caused by a low voltage condition.

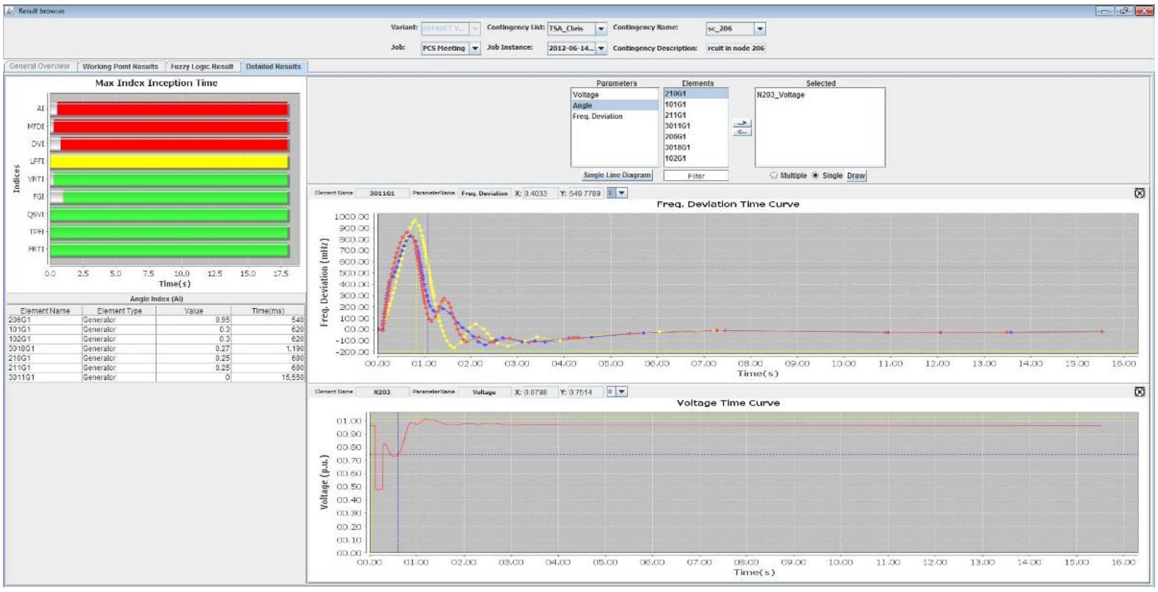

Figure 13: Fourth layer of DSA results visualization

Additionally to the above mentioned visualization layers, the results can also be visualized on single line diagrams with colouring of elements and isosurfaces (see Figure 14), i.e. surfaces that represent points of a constant value within a volume of space..

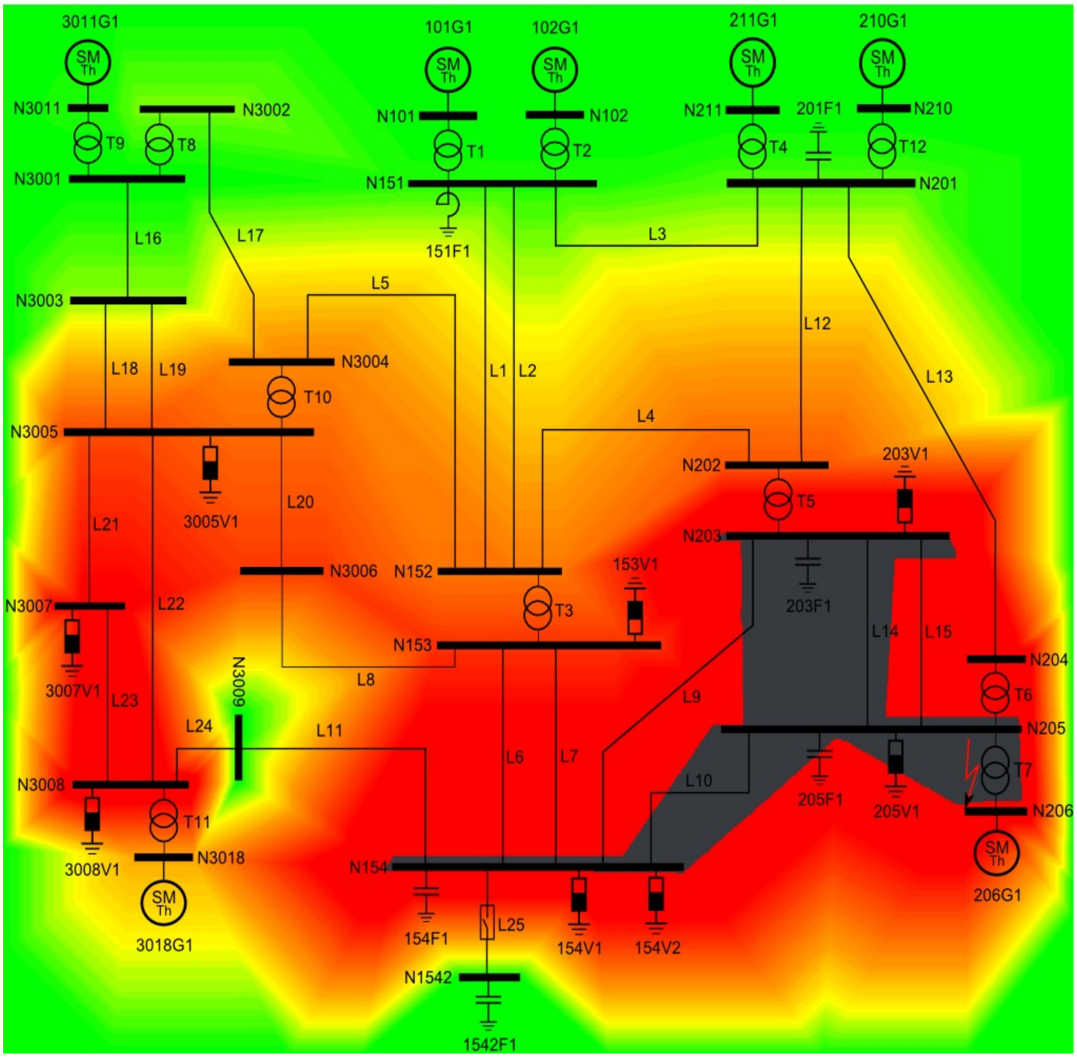

Figure 14: Single line diagram with underlying isosurfaces representing DSA results

4. Conclusion and Outlook

The User Interfaces described in this paper basically make use of various graphical means that capitalise on the human ability to quickly understand forms and colours, rather than abstract digits. In all cases vector diagrams – in the broadest sense – are used for the primary visualization; however, secondary and tertiary layers are also available to display more detailed information, then mainly providing stable-type displays. The largest amount of data will be available when an operator performs a Dynamic Security Assessment. All visualizations can be realised with off-the-shelf graphics libraries and then be deployed on the control centre panels.

Goal of further development is a better UI integration of the above described three approaches, as in the control centre of the future all three approaches will exist in parallel to each other, and they will offer complementary information for the operator and thus support him in finding answers to the different kind of tasks he/she has to deal with during operation. Such tasks can be related to the actual point of time or they can be of preventive nature, for example to avoid the risk of a blackout. The first step of such a parallelism is the exchange of data between SIGUARD PDP and SIGUARD DSA, which is being realised in a development project at the very moment.

End of text

BIBLIOGRAPHY

[1] Eichler, R., Krebs, R., Lerch, E. and Wache, M. (2012) “Mitigating Risk of System Instability Caused by Fluctuating Renewables with Smart Transmission Grid Applications” (Paper A154, CEPSI 19th Conference on Electric Power Supply Industry, Bali, Indonesia, 15-19 October 2012).

[2] Eichler, R., Krebs, R., Savulescu, S. C. and Wache, M. (2011) “Early Detection and Mitigation of the Risk of Blackout” (CIGRE International Symposium "The Electric Power System of the Future - Integrating Supergrids and Microgrids in Transmission Grid Operation ", Bologna, Italy, 13-15 September 2011).

[3] Buchholz, B.-M., Krebs, R., Rudion, Z. and Sassnick, Y. (2008) “Vision 2020 – Security of Network Operation Today and in Future. German Experiences.” (Proceedings of the IEEE PES, GM, 20-24 July 2008, Pittsburgh, USA).

[4] Savulescu, S. C. (2006) “Fast Assessment of the Distance to Instability” (In Real Time Stability in Power Systems, Springer, Norwell, MA, USA).

[5] Venikov, V. A. (1977) “Transient Processes in Electrical Power Systems” (Edited by V. A. Stroyev, English Translation, MIR Publishers, Moscow, Russia).

[6] Savulescu, S. C. (2004) “A Metric for Quantifying the Risk of Blackout” (Paper 04PS0294, presented at The Real-Time Stability Challenge Panel, IEEE Power Systems Conference & Exposition 2004, New York, New York, 10-13 October 2004).

[7] Van Cutsem, T. and Vournas, C. (1994) “Voltage Stability of Electric Power Systems” (Power Electronics and Power System Series).

[8] Kundur, P. and Balu, N.-J. (1998) “Power System Stability and Control” (McGraw-Hill Inc., New York, USA).

[9] Kerin, U., Bizjak, G., Krebs, R., Lerch, E. and Ruhle, O. (2009) “Faster than RealTime: Dynamic Security Assessment for Foresighted Control Actions” (Proceedings of the IEEE Powertech, 29 June - 02 July 2009, Bucharest, Romania).

[10] Lerch, E., Ruhle, O. and Kerin, U. (2008) “DSA-Visualisation Monitoring and Ranking of System Dynamic Behaviour” (In Proceedings of the 17th IFAC World Congress, July 2008, Seoul, Korea).

[11] Rudolph, A, (2011) “Function check, incorporation and performance test of indices to monitor the behaviour of electrical transportation systems by using the dynamic security assessment system SIGUARD®DSA” (Master Thesis, Institut für Technologie- und Wissenstransfer, Hochschule Mittweida, Germany).