



Speed-Up Voltage Stability Assessment Using Cluster Computing

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KEYWORDS

Client-server systems, Contingency simulation, Network observer, Parallel processing, Power system dynamic stability, Time domain analysis, Voltage stability.

ABSTRACT

Dynamic stability assessment is always more time consuming as the static approaches. Particularly voltage stability analysis demands a large amount of computing power because of the higher degree of model details and the longer simulated time span. In order to perform voltage stability analysis during operation and to help the operator with the results to make the right decision, these analyses have to be performed rapidly within a pre-defined duration of, for example, 15 minutes. The stability analysis is mainly characterized by contingency simulation, which can be done in parallel by nature. In this paper the approach of dynamic voltage stability assessment is described and the parallelization process will be presented.

1 INTRODUCTION

Today's power systems are utilized more as they were actually planned for. Several reasons for this development can be found. Worldwide a liberalization process has taken place which forces the network operators to compete with each other, and, hence, raising the utilization of their equipment to be more profitable. At the same time neighboring transmission system operators interlinked their systems electrically in order to enable cross border energy trading. This leads to long distant energy transports and to congestions on the tie lines of the interconnected systems.

Another reason for the increased stressing of the power systems is the political effort of several countries to reduce the carbon dioxide emissions, and to reduce the dependency on fossil fuels. Especially in Germany, the renewable energy act (EEG) [1] has led to a rapid increase of the number of distributed generators. From these generators the largest share is held by the wind generators. These generators are located where the natural resource is available, which is not always close to the load centers. Hence, this development also leads to long distance energy flows for which the system was not designed. The recent blackouts in America and Europe, with the last in Brazil, prove this thesis.

Fig. 1 represents the power system in relation to its operational boundaries. The optimal operating point is in the middle of the coordinate system with the three axes: reliability, profitability and ecology. However, the power system is pulled closer to the boundaries by the forces explained above. When approaching these boundaries, it is essential for the system operator to know exactly where the limit is and how far the system is from this limit. This is pointed out by the left and right side of Fig. 1. The left side shows the boundaries as a diffuse or foggy line, whereas the right part of the figure shows a sharp boundary and a smooth approaching.

The instrument to identify the boundary as exact as possible is the dynamic security assessment

system (DSA) [2]-[5]. The structure of a DSA system is shown in Fig. 2. Therefore, such a system should cover the analysis of transient stability, small-signal stability and voltage stability phenomena, as well as the analysis of the protection security.

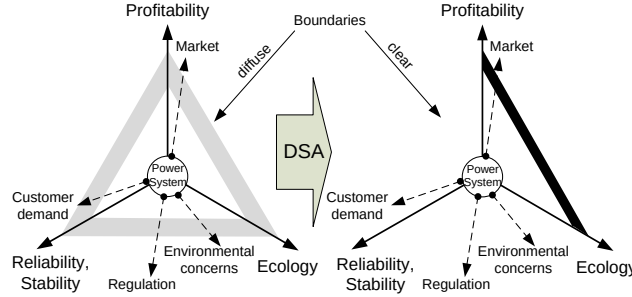


Fig. 1: Power system operation, boundaries and main forces pulling the system towards the limits with and without dynamic security system

Dynamic voltage stability assessment is the computationally most expensive part of the DSA, because of the numerous additional long term dynamics, which can be neglected during transient stability assessment.

In this paper the general dynamic voltage stability assessment approach, as realized within this DSA system, will be presented in section II. The parallelization of the power system simulation tasks is explained in section III. The paper closes with a summary and an outlook.

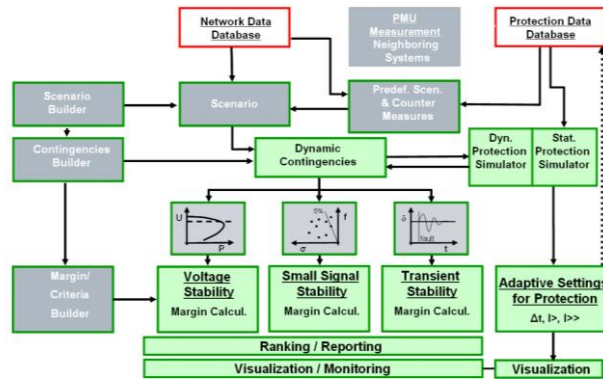


Fig. 2: Structure of DSA system

2 DYNAMIC VOLTAGE STABILITY ASSESSMENT

2.1 General Remarks

Voltage instability is, by definition, caused by the inability of the generation and transmission system to provide the reactive power, needed to satisfy the load demand, while keeping the voltages near nominal values. The driving force for instability is the load recovery after severe contingencies occurred. The limiting factors are the loading limits of the transmission equipment and the regulation limits of voltage controlling devices like tap-changing transformers, compensation devices, and excitation systems of synchronous generators.

In dynamic voltage stability assessment, the behavior of the power system after N-1 contingencies like generator or line outages is simulated in time domain. This way, the pre-contingency working point can be considered as voltage secure, if no contingency led to instability, or voltage as insecure, if any credible contingency causes the system to become instable. The last voltage secure working point is called the secure operation limit, SOL [6]. To be able to observe all the abovementioned forces and limits, and finally voltage instability, the dynamics of these elements have to be modeled. Fig. 3 shows the power system model adjustments that have to be done prior to voltage stability assessment. The left side of the figure shows the most commonly available dynamic power system model used for transient analyses. On the right hand side the modifications are marked in red.

2.2 Unattended Contingency Simulations

In order to be able to perform the DSA analyses in an online time frame of, for example, 15 minutes, all the simulations, results evaluations, and preparing for visualization has to be done automatically. This means that the network operator is not required to decide which part of the system has to be observed and whether the contingency is severe or not. This is the reason a network observer has been developed, which observes the whole power system during integration, and focuses only on the most affected system areas and elements.

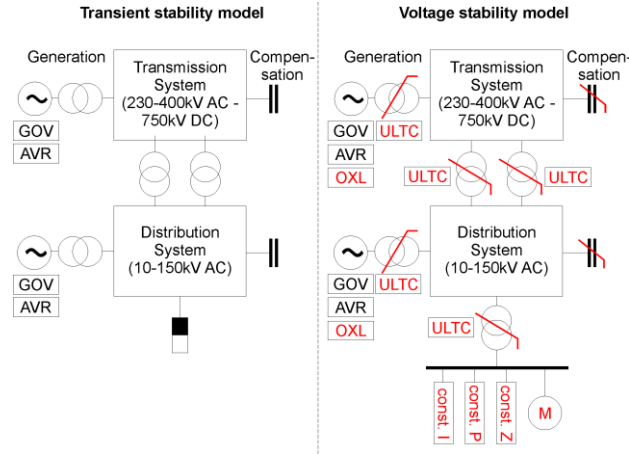


Fig. 3: Comparison of the most common transient stability dynamic power system model and the dynamic model used for voltage stability assessment

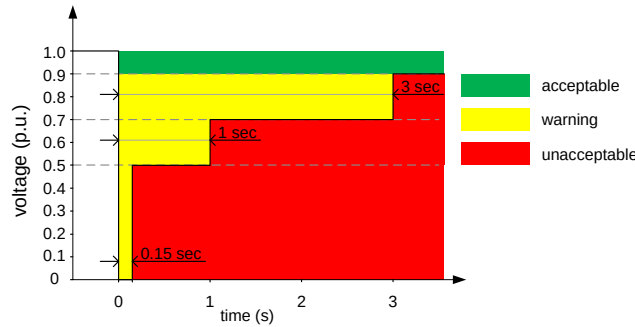


Fig. 4: Voltage security constraint for network observer for generation bus.

The network observer constraints define when an element gets the focus of the network observer. These constraints are rules, set by the network operator, which reflect the operation handbooks [7], [8], power quality norms, or operator experiences. Such a constraint is shown in Fig. 4 for a generator bus. This constraint is taken from the grid code of a German network operator [9]. It marks the operational areas as ‘acceptable’ (normal operation), ‘warning’ (abnormal operation), and ‘unacceptable’. In the grid code, it is defined, that the generator is supposed to stay connected to the network when the ‘unacceptable’ area has not been entered. Such constraints can be defined for each kind of network bus, equipment, and load point.

Additionally to the security constraints, margins, sensitivities, and reactive power regulation reserves are calculated during time domain simulation. As the voltage collapse margin, M_{ZLine} , the line loading of each line is observed. Similar as in a two node network with a sending and receiving end, where the loadability limit is reached when the magnitude of the load impedance is equal to the magnitude of the line impedance, voltage instability occurs also in a meshed system when this criterion is reached at one single line of this system. Hence, the equivalent load impedance at the terminals of each line is permanently calculated, and compared with the line impedance. If the magnitudes of both impedances are equal, the contingency is considered as instable.

Similar margins are proposed in [10] and [11]. In [10] the so-called basic line stability index

(BLSI) is introduced. This index is derived from the power flow equations and indicates the nose of the system P-V curve, where the slope is infinite. The value of this index is one when the nose is reached and higher than one when a margin to the nose exists. It can not take values below one, which makes it hard to distinguish marginally stable (just before nose point) from unstable cases.

The network observer permanently writes the important observations to a text file. In this text file only violations of the constraints, or under-run of margins or reserves are saved together with the element name and time of occurrence. By analyzing this text file, one can reconstruct exactly what, where, and when did something happen during the simulation.

Table I: Meaning of the values of the voltage security index VSI

Index value	Corresponding events
0	no parameter violations were observed
0.25	voltages or currents have been in warning area
0.5	zero reactive reserve at any generator or compensation, tap-changer at limit is reached or motors have stalled
0.75	voltages or currents have been in unacceptable area
1	voltage collapse ($M_{ZLine}=0$)

From this information the severity of the contingency can be evaluated by calculating the voltage security index VSI. This index can take on five different values depending on the violations of the security constraints (see Table I). The VSI is used to rank the contingencies to be presented to the network operator. The most severe contingencies have to be monitored at first, whereas the cases with a VSI equals to zero are not at all interesting for the operational decisions.

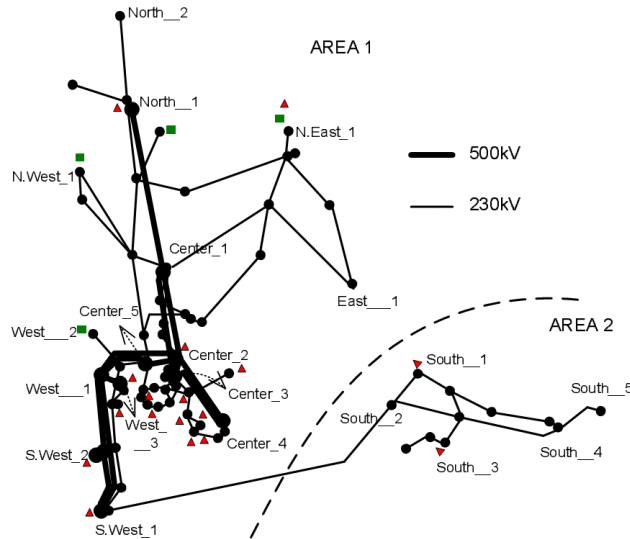


Fig. 5: Test system topology of the 500 kV and 230 kV voltage level [12]

2.3 Simulation of Future Working Points

The degree of voltage stability of a power system is always depending on the direction of the system trajectory. In the proposed contingency simulations it is possible to determine whether the pre-contingency working point is secure or not. Furthermore, with the calculated margins, reserves, and sensitivities it is possible to qualitatively say if the system is close to the SOL or not. Because of the strong nonlinearity of power systems it is not possible to quantify, e.g. a load power margin, when only the current working point is considered as the pre-contingency working point. Hence, the DSA system should be able to consider also unplanned working points that will most probably occur in the

near future (30 – 120 min.).

These unplanned future working points could be caused by the deviations from the day-ahead forecasts of the wind power in-feed, or unforeseen, though, postponable topology changes. With the knowledge of the degree of security of these working points, the operator can decide whether to allow these working points or to avoid them.

2.4 Application on Test System

The proposed dynamic voltage stability assessment system was tested on a national transmission system with 119 generators, 527 lines, 300 load points and 440 tap-changing transformers. This power system consists of 500 kV, 230 kV and 115 kV voltage levels. The total load of the system in the base case is around 20 GW. The topology of the 500 kV and 230 kV level of the test network is presented in Fig. 5.

Starting from the base case, the system trajectory was simulated by increasing the load demand at all load points equally in small steps. This resulted in 35 possible, future working points as described in section 2.2.3. For presentation purpose the proposed contingency analysis was performed for all N-1 contingencies for all 35 working points.

Fig. 6 shows the results for all N-1 230 kV line contingencies in form of a color matrix. The x-axis represents the contingency (in this case 88 contingencies were simulated). The y-axis indicates the working points, whereas the working point 1 represents the base case. The y-axis can also be thought of as a time axis when each working point can be assigned to a certain time in the future. The colors of the rectangles in the matrix represent the value of the VSI as shown on the far right side of Fig. 6.

One can easily see that when proceeding on the y-axis from the bottom (base case) to the top (increasingly stressed system), the degree of stability becomes worse. As stated in Table I, a VSI of zero (green) is not critical at all and also a VSI of 0.25 (yellow) means only warning. Hence, all the green and yellow cases can be considered as acceptable. Orange, red and black, on the other hand, must be avoided. In this special case, the operator could easily allow the first ten working points, but should investigate preventive or remedial measures to avoid voltage problems in the red cases, when further operation (above 10th working point) is required.

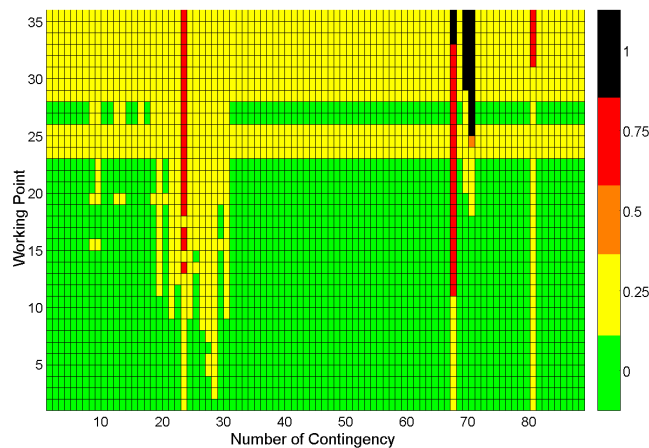


Fig. 6: VSI color matrix of all N-1 230 kV line outages and 35 working points in the DSA test network

3 PARALLEL COMPUTING

3.1 General Remarks

The results presented in Fig. 6 are based on excessive simulations. The figure shows 88 contingencies for 35 working points, which means 3080 simulations have to be run. One contingency simulation of five minutes real time takes about one minute and 17 seconds for the test power system on a standard PC. To simulate all the 3080 contingencies, a single PC would have to simulate for 66 hours. This, of course, is too much time for an online application. Even if the DSA system wants to look only two working points into the future, it would have to run 264 simulations, taking more than

five hours.

In order to be still able to run the dynamic simulations within an online time frame of 15 minutes, ways and means have to be found to accelerate the dynamic assessment process. Principally, there are three ways to do this:

- simulation acceleration,
- contingency filtering,
- increasing of computation power.

The first two are shortly mentioned in this paper and the third will be discussed in more detail. Nevertheless, all three methods should be considered in an online DSA system.

When speaking of ‘simulation acceleration’ the reduction of the single contingency simulation is meant. In the abovementioned example this means to reduce the one minute and 17 seconds. This can be reached in several ways:

- model reduction,
- variable time step,
- early abortion,
- skipping of repeated routines of the simulation program.

The potential of the above measures to save computation time is actually very high. For example, reducing the power system model by simplifications of the load model in regions where the contingency has no impact, could halve the simulation time with respect to the full model shown in Fig. 3.

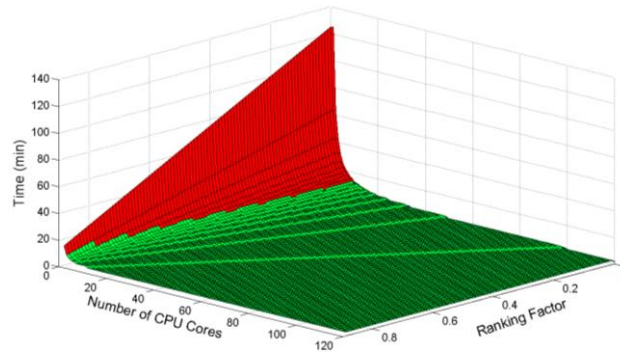


Fig. 7: Potential of DSA acceleration by increasing the number of CPU cores and reducing the number of simulations by contingency ranking (filtering), when a maximum of 100 contingencies have to be simulated

Contingency filtering is also a very effective way to reduce the security assessment time [13]. When looking at the Fig. 6, the potential is obvious. From the 88 contingencies, only five contingencies are causing severe problems. This filtering should be done by faster screening methods or by using the experience of the network operator.

The most promising way to accelerate the DSA process is to increase the computation power by performing the contingency simulations in parallel on a server cluster. The parallel simulation of different contingencies is feasible because their execution is completely independent of each other.

Fig. 7 shows the potential of accelerating the dynamic stability assessment by applying the two measures: increasing the number of CPU cores (x-axis) and reducing the number of contingency simulations by means of contingency ranking or filtering (z-axis). The figure is drawn for a maximum number of 100 contingencies. One can see that the simulation time is linearly depending on the ranking factor (high factor = strong reduction of contingencies). Increasing the number of CPU cores, on the other hand, causes a strong reduction of simulation time at the beginning with saturation when the number of CPU cores comes into the region of the number of contingencies. The area shaded with red color indicates simulation times higher than the time window of 15 minutes, whereas the green color indicates lower simulation times.

It can be shown, that 100 contingencies can be simulated dynamically within 15 minutes with less than 20 CPU cores. For this study a server cluster of ten double core industry PCs was employed. Because the hardware consists solely of off-the-shelf products, the costs for such a system are moderate. In this case the specific costs per CPU core are around 550 € including the 19" Server Rack,

an uninterrupted power supply unit (UPS) and the network equipment. Hence, the investment costs for a system with 100 CPU cores would be around 50000 €.

3.2 Structure of Developed Parallel Computing System

The advantage of parallelizing the contingency simulations is that only a communication and simulation management system has to be developed, while relying on a proven power system simulator. In this study the power system simulator PSS[®]NETOMAC from Siemens is used. The developed software principally consists of three parts: the DSA client, the parallel computing client (PCC), and the parallel computing server (PCS). The hardware structure is based on the client-server principle.

The general structure of the parallel working DSA system is shown in Fig. 8. The DSA center receives the current working point (WP) data and, if available, the short-term forecasted system trajectory from the control center. This information is processed by the DSA client. The DSA client then selects a set of contingencies and the future WPs which have to be simulated.

Additionally, the DSA client contains the information about the power system model. This means that here all the system specific data like equipment names, controller data and the system model structure must be kept up to date. If, for example, the outage of a generator has to be simulated, the DSA client knows where to find this generator in the system model and how the outage has to be initialized. This information is passed to the PCC in an abstract way. This way the software below does not have to be engineered when the power system model changes.

The client and server programs PCC and PCS are written in Java (Version 6 SE) [14]. The communication layer, remote method invocation (RMI), is part of the Java language specification. The RMI allows for not only exchanging data between the client and servers, but also for passing Java objects, containing executable functions, to the server. Hence, the server program PCS can be kept simple, while its functionality is managed by the client program.

The client program PCC manages the list of servers by updating their availability and capability (number of CPU cores, speed of CPU, etc.). This makes the system tolerant against network (LAN) failures, and flexible to use not only special cluster servers but also, if required, office PCs that can provide temporal computation power.

If the DSA client demands for contingency simulations, the PCC builds the contingency description and the server functionality object, and passes it to the server. Afterwards, the server knows how to change the power system model to simulate the specific contingency, performs the changes, and starts the simulation on the power system simulator.

After the simulation with PSS[®]NETOMAC, the text file, written by the network observer, is pre-analyzed by the server to provide the VSI and a graphical representation of the simulation results in form of a colored system matrix [15] and a Google[™]Earth KML [16] file to be visualized to the operator. The text file from the network observer and the pre-analyzed results are saved in a database which can be read from the control center.

The visualization of the DSA results is planned to be realized within the real time monitoring system, e.g. SIGUARD[®]-PDP [17], running in the control center. If any contingency simulation reveals stability problems, remedial have to be triggered. Hence, the DSA client can receive direct orders from the control center to pre-simulate a contingency, applying certain remedial measures (RM) like load shedding to investigate if the measure can be successfully applied.

4 CONCLUSIONS AND OUTLOOK

The need to assess the exact level of power system stability is becoming apparent as the loading of the equipment and the risk of blackouts increase. It could be shown, that with dynamic security assessment the operational boundaries can be clearly identified. Therefore, all aspects of power system stability have to be considered. Voltage stability is one of these aspects and requires comprehensive modeling. The results of voltage stability analyses on a test system show that the information, available from time domain simulations, can help the operator to take the right decision in case of an insecure system situation. The possibility to pre-simulate certain remedial measures makes it easy to trigger efficient measures in case the contingency actually occurs.

The surplus of information from the time domain simulations is bought with a large demand of computation power. The online time frame of 15 minutes can either be reached by massive

simplifications of the power system model, or by increasing the computation power. The latter can be employed very effectively because the contingency simulations, performed during the stability assessment, can be done in parallel.

It could be shown that using off-the-shelf computer hardware a flexible and powerful computing cluster can be built. The developed software manages the parallel contingency simulations in a client-server fashion and uses an established and reliable power system simulator.

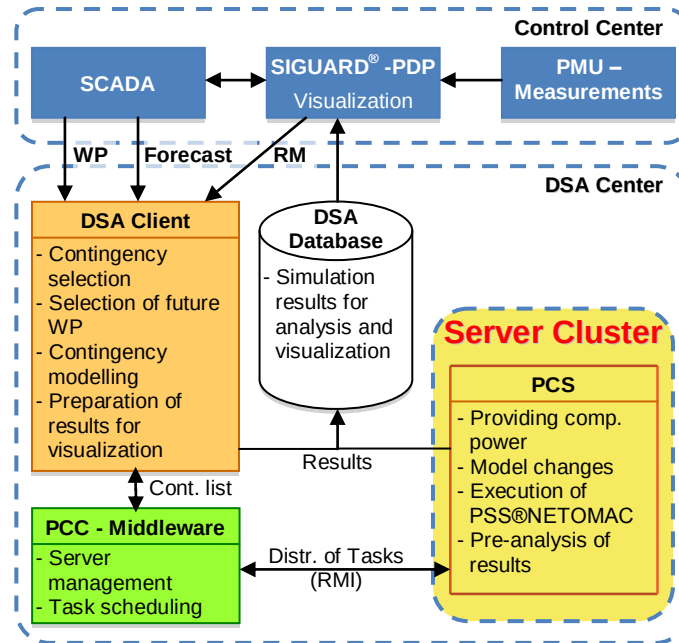


Fig. 8: Software and communication structure of client-server system for parallel contingency simulations in the scope of an online DSA system

In future works, the behavior of the protection system should be included in the power system model [5], [15]. This way the results would be able to account for cascading outages owing to protection tripping. The requirement for such an implementation is that the generic protection models can be parameterized by the protection settings from the network operator and that they are readily available.

ACKNOWLEDGMENT

The authors gratefully acknowledge R. Breunung for his work on the original version of this document.

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