European Network of
Transmission System Operators
for Electricity

SPD DSA Task Force
Dynamic Security Assessment (DSA)

RG-CE System Protection & Dynamics Sub Group

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Contents

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1. Introduction

1.1 Normative reference

The Article 38 of the System Operation Guideline states the following related to Dynamic Stability monitoring and assessment:

Article 38

Dynamic stability monitoring and assessment

1. Each TSO shall monitor the dynamic stability of the transmission system by offline studies in accordance with paragraph 6. Each TSO shall exchange the relevant data for monitoring the dynamic stability of the transmission system with the other TSOs of its synchronous area.

2. Each TSO shall perform a dynamic stability assessment at least once a year to identify the stability limits and possible stability problems in its transmission system. All TSOs of each synchronous area shall coordinate the dynamic stability assessments, which shall cover all or parts of the synchronous area.

3. When performing coordinated dynamic stability assessments, concerned TSOs shall determine:

(a) the scope of the coordinated dynamic stability assessment, at least in terms of a common grid model;

(b) the set of data to be exchanged between concerned TSOs in order to perform the coordinated dynamic stability assessment;

(c) a list of commonly agreed scenarios concerning the coordinated dynamic stability assessment; and (d) a list of commonly agreed contingencies or disturbances whose impact shall be assessed through the coordinated dynamic stability assessment.

4. In case of stability problems due to poorly damped inter-area oscillations affecting several TSOs within a synchronous area, each TSO shall participate in a coordinated dynamic stability assessment at the synchronous area level as soon as practicable and provide the data necessary for that assessment. Such assessment shall be initiated and conducted by the concerned TSOs or by ENTSO for Electricity.

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5. When a TSO identifies a potential influence on voltage, rotor angle or frequency stability in relation with other interconnected transmission systems, the TSO concerned shall coordinate the methods used in the dynamic stability assessment, providing the necessary data, planning of joint remedial actions aiming at improving the stability, including the cooperation procedures between the TSOs.

6. In deciding the methods used in the dynamic stability assessment, each TSO shall apply the following rules:

(a) if, with respect to the contingency list, steady-state limits are reached before stability limits, the TSO shall base the dynamic stability assessment only on the offline stability studies carried out in the longer term operational planning phase;

(b) if, under planned outage conditions, with respect to the contingency list, steady-state limits and stability limits are close to each other or stability limits are reached before steady-state limits, the TSO shall perform a dynamic stability assessment in the day-ahead operational planning phase while those conditions remain. The TSO shall plan remedial actions to be used in real-time operation if necessary; and

(c) if the transmission system is in the N-situation with respect to the contingency list and stability limits are reached before steady-state limits, the TSO shall perform a dynamic stability assessment in all phases of operational planning and re-assess the stability limits as soon as possible after a significant change in the N-situation is detected.

In following chapters, the guidelines for the correct interpretation of this article are given

2. Dynamic Security Assessment

Power System Stability is the ability of an electric power system to regain, for a given initial operating condition, the state of operating equilibrium after having been subjected to a physical disturbance, with all system variables bounded in such a way that preserves the system integrity.

In the last years, the European electricity sector has, changed drastically. Sector unbundling, system extension, market integration, high capacity installation of renewable energies (mainly wind and solar), etc. have led to an increase in the distance and uncertainty of the power exchanges, loop flows through neighbouring countries, decrease of system inertia and typical synchronous machine controls (such as automatic voltage regulator and governors), etc.

Some real incidents[1] demonstrated that the conventional concept of steady state security verification (i.e. load flow) cannot sufficiently to guarantee the system integrity in such situations. In addition, large penetration of inverter based power units and loads implies a change of system dynamic behaviour and creates the need to give to Control Room staff new instruments for additional decisions.

Therefore, the power system stability is becoming a crucial issue for planning and operation and might impose operation constraints for ensuring system operation security in the future.

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[1]https://www.entsoe.eu/Documents/SOC%20documents/Regional_Groups_Continental_Europe/20150921_Black_Out_Report_v10_w.pdf
https://www.entsoe.eu/fileadmin/user_upload/_library/publications/entsoe/RG_SOC_CE/Top7_110913_CE_inter-area-oscil_feb_19th_24th_final.pdf

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As a consequence, the time frame of the needed dynamic analyses has to broaden, from long term planning studies to the analysis of scenarios closer to real time. At the same time, new aspects of system stability (such as small signal stability – related to inter-area oscillations …) have to be addressed in these studies.

DSA may be oriented to different issues depending on the time horizon in which they are performed.

- Long term DSA (in the scope of year(s)) studies may give feedback to network planning and are the basis for the elaboration of generation and demand Connection Codes. Their objective is to assess:
  - Critical Fault Clearing Times
  - Transient Stability
  - Voltage Stability
  - Loss of synchronism
  - Poorly damped interarea oscillations (small signal analysis)
  - Short term exceeding of electrical quantities such as voltages, currents, angles etc.
- Medium term DSA (monthly, weekly, day ahead approach) can get useful information for the coordination of maintenance programs and the feasibility of operation programs, providing the right grid configuration to avoid potentially risky situations at system operation, defining preventive system restrictions, post-event operative measures, dispatching of automatic measures (switching on and actions of special protection schemes).
- Online DSA gives support to system operation in real time. Results have to be displayed in a simple and meaningful manner to operators, as they invoke operational decisions and actions.

In all cases, a good balance between the quality of the system model and the computation time is of great importance. Regular validation of the system model under notable network events and situations is of great help in order to maintain it reliable.

Different stability phenomena lead to different modelling requirements:

- Voltage stability studies need representing the key characteristics of the transmission and distribution system at regional level.
- Transient stability studies use the representation of loads as constant impedance or constant current. The model has to represent in detail a region or a country, a reasonably detailed model for an interfacing area, and a reduced simplified model for the rest of the system (equivalents).
- Small signal stability involves the whole system; therefore, the use of complete models of systems is necessary. The Initial Dynamic Model (REF) is a first approach to this kind of studies at Continental European level, although, more accurate models are necessary to improve the reliability of the results.
- Frequency stability issues (such as inertia studies, under-frequency load shedding, etc.) can be addressed by means of a single busbar model.

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3. Functional Architecture

3.1 Data flow and functional blocks

In Figure 1 the typical DSA structure and data flow are shown. In real time implementation, the main source is SCADA / STATE ESTIMATOR that ensures the first, feasible and coherent starting point. This preliminary data processing is not self-sufficient to guarantee a usable starting point; in fact, there is a need for a generic "**data preparation**" functional box in which several processing is executed:

1. Grid definition: the grid imported from the state estimator needs to be connected to the external system (i.e. the grid under control by a single TSO must be connected to the rest of CE system or to an equivalent). As an option, the grid could be a merge of different compatible TSO snapshots ("other systems'" blocks) or a mix (i.e. TSO's grid from the state estimator linked to an equivalent built on DACF files). Several techniques and approaches are adopted by different TSOs.
2. Link with dynamic models: static scenario must be completed by inserting dynamic models:
    a. Prime movers, Power System Stabilizers, Automatic Voltage Controllers (with limiters)
    b. Control (secondary frequency control, secondary and tertiary voltage regulation)
    c. Protection devices (static and dynamic electrical components). In these applications, simplified modelling for the protection devices is used: e.g. generator out of step, under/over voltage protection of generators, loss of synchronism in interconnections, are normally used in the simulations. Usually, the rest of the protection equipment is not modelled and, when a contingency is simulated, its expected behaviour (action time and circuit breakers affected) is taken into account in the event definition instead.
    d. Load shedding relays
    e. Special Protection schemes
    f. If Optimal Reactive or Active power flow calculation is performed, some information from market is needed in addition (i.e. costs, offers, …)

DSA is also interfaced with "offline tools"; this means that the software must be capable to analyse an "offline" predefined scenario (this refers mainly to planning offline activities) or evaluate an existing scenario properly modified offline in order to evaluate a particular issue.

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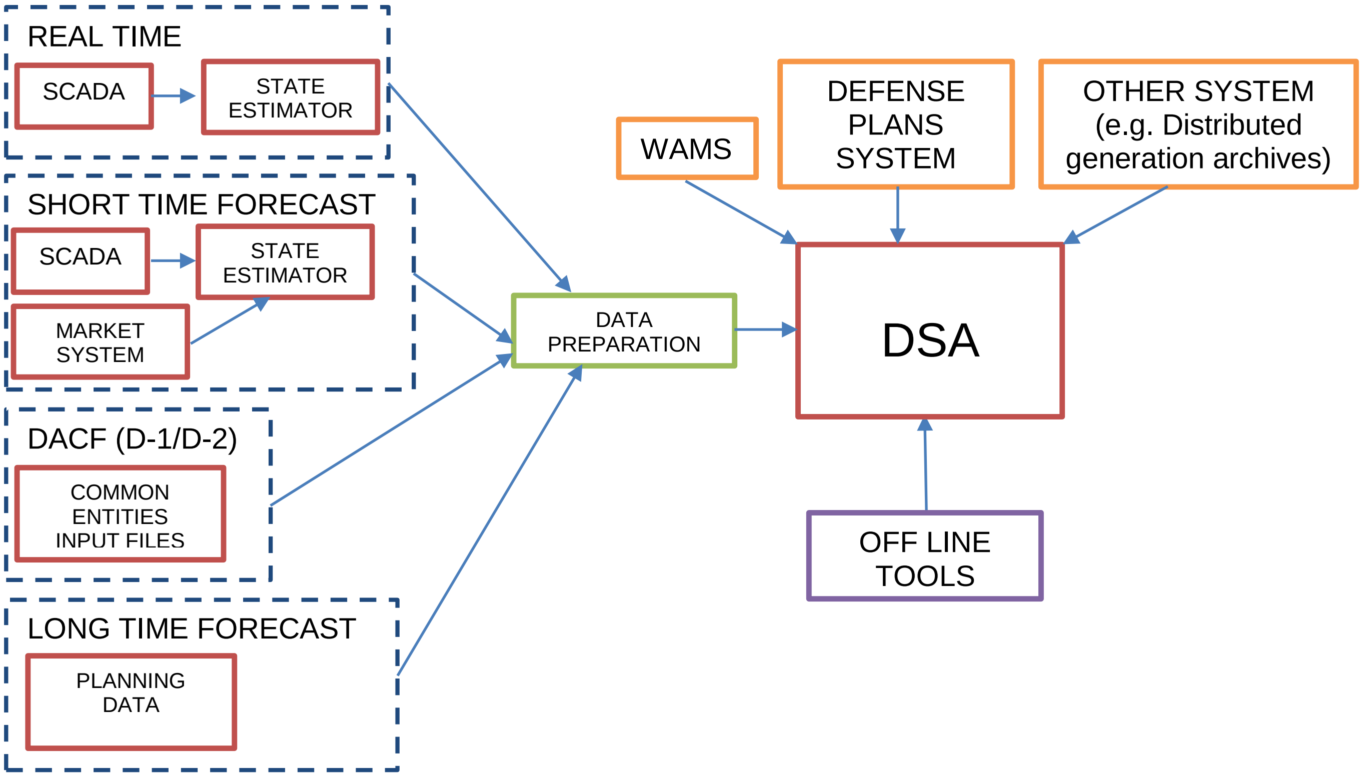

Figure 1 – Typical DSA structure and data flow

3.2 Key aspects for a DSA design

3.2.1 Key aspects:

A valid functional architecture must be designed to answer one key question:

What is an adapted tool for the operator such as he is able to implement the right action at the right moment to keep the grid safely in operation?

To answer these questions, the DSA designer must take into account several factors:

3.2.2 The time frame

Time frames: “Online” DSA (with latest available snapshots), close to real time (with the latest available forecasts), in day ahead, week ahead and even in the long term for yearly dynamic studies, outage planning or grid development.

For the operator, working closer to real time has the advantage of making him work in a context of low level uncertainties, whereas working in a further time frame gives access to a broader panel of leverages. In any case, the time frame is conditioned by the availability of appropriate data. On the other hand, it must also be considered that some additional elements can decrease the level of confidence, like low level of observability of dispersed generation or unexpected forecast errors. Moreover, the market can generate a deviation from the schedule.

3.2.3 The input data:

As described in previous chapter, a lot of different sources are available to be properly processed in a consistent way (day ahead forecasts, intra-day forecasts, snapshots, equivalent grids).

It must be underlined that the horizon of the selected study has an influence on data and dynamic models.

The selected data must be as much as possible purified from uncertainties or, alternatively, the simulation results must be properly adapted to take into account the uncertainty elements.

An important emerging problem is dispersed generation representation; the correct model must take into account the zero contribution to system inertia, the regulating features – if present (power frequency regulation), the tripping frequency of these devices (i.e. 50.2 Hz), their behaviour during voltage dips (trip or insensitivity to voltage dips), and a correct estimation or measurement of their actual production (currently, the direct measurement of dispersed generation is not available to all SCADA systems; therefore, in such an application, the production of dispersed generation is an estimated quantity with a certain degree of uncertainty).

In case of internal TSO dynamic studies, the availability of data is generally not an issue. It relies on internal data management processes that have been set up to answer TSO's needs for static and dynamic security assessment, which themselves depend on the tools used by each TSO.

In case of coordinated studies, data exchange of snapshots and forecasts with the same time stamp is crucial, especially for automated processes where the quality of the studies depends on the availability of neighbour's data for a given time stamp.

To that, some ENTSO-E WG are working together to harmonize the release of data at different time horizons as well as data formats:

3.2.4 Dynamic Models Selection

The selection of models is influenced by following factors:

- Available input data and related uncertainty
- Horizon of simulation (seconds, minutes, hours)
- Phenomena to be assessed

About first point, as well-known from operation experience, the input scenario and confidence with models and related parameters have a crucial role in the simulation; this means that a continuous validation work must be done to verify and fine-tune models, also using more innovative monitoring systems like WAMs.

The selected horizon of simulation is crucial in order to maximize the performance of the system; a preliminary decision is the selection of phenomena that must be studied. This is the most delicate issue because a wrong choose will influence the quality of information that will be presented to the real time Control Room people.

In Figure 2 we can note that to different phenomena different models and different time horizons correspond.

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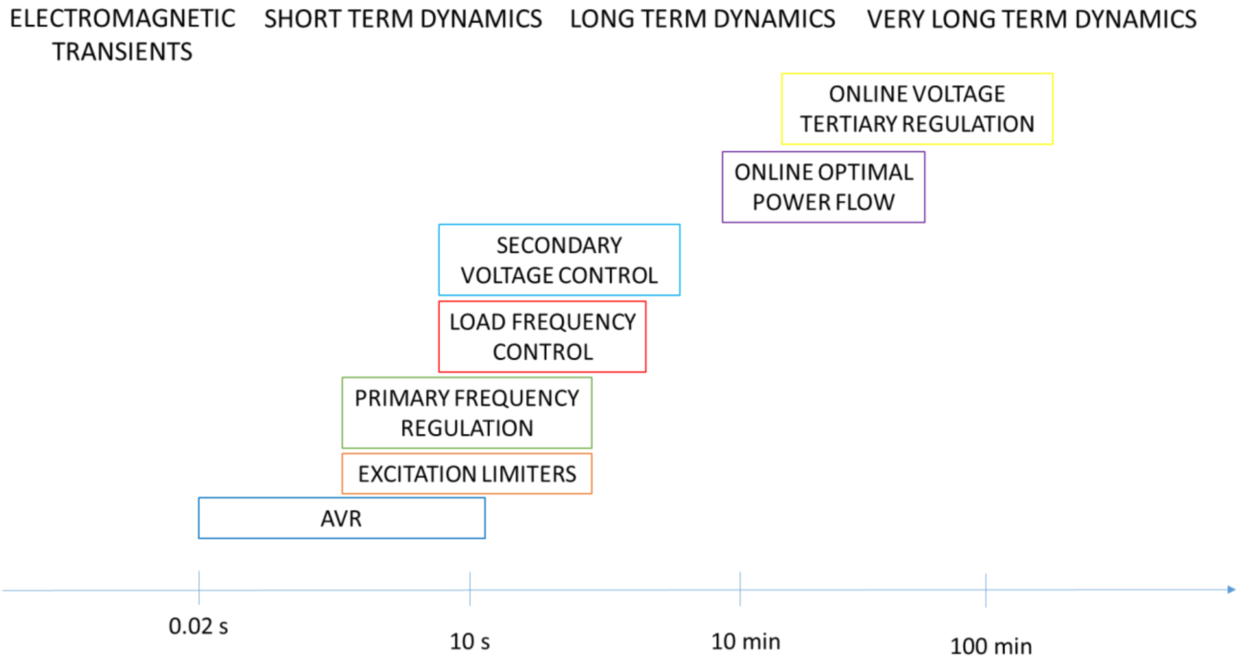

Figure 2 – Dynamic phenomena vs time horizons

Some proper hypotheses can be adopted; for example, primary regulation transients are by definition "mean frequency transients", so the voltage dependence of system elements or very fast regulation devices could be simplified. At limit, the whole grid could be represented as one or more single busbar models.

About voltage stability, as second example, a very detailed model shall be adopted, but, being a local phenomenon, the rest of system could be simplified.

If focus has to be given on slow regulations (i.e. tertiary voltage regulation or boiler regulation in conventional power plants), the description of fast regulators could be drastically simplified due to large time constants (minutes, hours).

In the literature there are numerous references to numeric algorithms that are able to "modify" the grid models during the simulation in order to adapt them from the short term up to the long term behaviour. In general, certain attention must be paid to avoid numerical problems (and false indications) that could arise from this approach.

Alternatively, a more rigid strategy could be selected in parallel for short term and long term simulations differentiating the models for different time horizons.

3.2.5 The steady state condition

Under the name of steady state condition we have to include a lot of adjustments that are needed to reach the correct initial situation; the reaching of this condition is very insidious, because an imperfect scenario preparation could generate a wrong initialization of state variables and wrong results during the simulation.

Therefore, the "data preparation module" in addition to the functions previously described must:

- Perform a bad data analysis and correction
- Modify all the dynamic inconsistencies (i.e. fictitious synchronous machines at operating conditions not physically feasible from dynamic point of view)

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- Detect and eliminate saturation of state variables near to saturation limits (i.e. on governors or exciters)

At the end, heuristic methods like “monitor gradient of state variable” can be used to obtain a good steady state condition.

3.2.6 Exceptional transient conditions

During the simulation of large disturbances some very critical numerical situations can arise. Especially when the system goes in direction of splitting, the main electrical variables could reach values completely out of validity bounds of the model.

The classical voltage/frequency dependent model of loads can serve as an example.

In these particular conditions it is important to (i) choose an automatic criterion that decides if the system matrix starts having an anomalous scarcity or in some zones the calculated values go in very out of bounds directions, (ii) detect, cluster and “switch off” these zones declaring them “lost or in a probable black out”, and (iii) proceed with the simulation.

Also in this case the “switching off” conditions must be defined in the projecting phase of DSA.

3.2.7 Dynamic simulation automatic ending time

Another important issue for DSA is to decide “when” a simulation has to be considered finalised. This apparently easy aspect is very critical in the reality. In fact, in such situations, the apparent steady state condition can hide a slow unstable transient that needs several simulation steps to be identified.

Therefore, we need a check list to declare the simulation finished; for example:

- The final voltage and frequency
- The status of gradients of all the state variables
- The permanent violation of saturation of regulation devices
- The distance from instable critical points

3.2.8 The identification of the contingencies

The contingency selection typically needs a mixed approach, following these rules:

- Predefined contingencies: well-known from experience and inserted in the contingency list manually or by automatic selection. I.e. N-1 or complex like load trip, power plant trip, busbar faults.
- Automatically derived contingency: it is a decision that DSA can derive contingencies from static N-1 evaluations. For instance, some techniques are currently available in order to estimate the cascading effects and decide on the most critical “starting” contingency.
- Operator contingency: based on current snapshot, the Operator must be able to “construct” a new contingency. For instance, forcing one or more adverse events into a scenario in order to check “what if”.

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3.2.9 The judgment of contingency

In real time DSA this is a very difficult task. There is no time to analyse the results manually and, in the Control Room, there is no power stability expert to support this analysis. Therefore, DSA must manage a list of evaluation criteria to give, at the end, a simple and fast indication to the operator in form of first level screening. Clearly, it must be possible for the user to navigate more deeply into the simulation to analyse the results in detail.

The typical criteria are:

- Limits of steady state values reached after the simulation (voltages, frequency, currents, exchanges on tie lines, …) and eventual violation of desired value levels
- Limits of transient values reached during the simulation (voltages, frequency, currents, exchanges on tie lines, …) and eventual violation of desired value levels
- Excitation or tripping of protections or Special Protection Schemes
- Intervention of Defense Systems
- Network Splitting during simulation
- Final Black out state of a part of the system
- Dangerous values of electrical (i.e. frequency gradient) or mechanical quantities (stress on turbines)
- Violation of security margins after the simulation (i.e. exhaustion of primary reserve or reactive reserve)

Each criteria can be weighted and evaluated for a final synthesis that must be displayed to the user. An example of “table of judgment” is reported in the following table.

INDICATOR	AND CONDITIONS		MEAN
REGFN	-0.01 Hz/s <= df/dt <= 0.01 Hz/s	49.9 Hz <= f <= 50.1 Hz	Steady state condition with the frequency in the range 50 Hz +-0.2%
REGUF	-0.01 Hz/s <= df/dt <= 0.01 Hz/s	f <= 49.9 Hz	Underfrequency steady state condition
REGOF	-0.01 Hz/s <= df/dt <= 0.01 Hz/s	f >= 50.1 Hz	Overfrequency steady state condition
UNFR	df/dt < -0.01 Hz/s	f < 49.9 Hz	Frequency collapse evolution
OVFR	df/dt > 0.01 Hz/s	f > 50.1 Hz	Uncontrolled overfrequency evolution
REGVN	-0.1 kV/s <= dV/dt <= 0.1 kV/s	380 kV <= V <= 420 kV	Steady state condition with the voltage in the range Vn +- 5%
REGUV	-0.1 kV/s <= dV/dt <= 0.1 kV/s	V <= 380 kV	Undervoltage steady state condition
REGOV	-0.1 kV/s <= dV/dt <= 0.1 kV/s	V >= 420 kV	Overvoltage steady state condition
UNV	dV/dt < -0.1 kV/s	V < 380 kV	Voltage collapse evolution
OVV	dV/dt > 0.1 kV/s	V > 420 kV	Uncontrolled overvoltage evolution
ISOKO			Not programmed islanding
BOUT		f = 0 Hz OR V = 0 kV OR Black out conditions	Black out conditions

3.2.10 The actions to be implemented and possible coordination

Firstly, DSA must be able to simulate, automatically or by request of the user, if he/she exists, a remedial action as a variation of the analysed contingency.

If possible, DSA must be able to suggest the most feasible solution, but it must be considered that the combinations of preventive and curative actions can be numerous while computation times are limited.

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The implementation of some of these actions might imply coordination with other TSOs. It is possible only if a threat for the security of the grid has been commonly agreed between the concerned parties.

In order to keep the system safe, TSOs have a set of available actions which they can apply if required according to security analysis results. The most common ones are topological measures, because the associated cost is low and the number of available efficient actions may be reduced for some critical cases. TSOs have also control actions such as voltage set points modifications and changing of transformer tap positions. HVDC links and FACTS also provide some new ways to act on the power grid.

Generation reallocation is one possible path, but with much higher associated costs. Monitoring the loading level of overhead lines is also used. Load shedding as a part of defence plans can be used in real time, mainly for peak load management, in a situation with low frequency in the power system.

Some actions are only used in a second step if the previous actions listed above are insufficient.

Different strategies are possible acting preventively or curatively. The use of preventive actions is recommended if not implementing them would lead to unacceptable post-fault transients with only available curative actions. The use of preventive actions could be expensive since they have to be implemented before a contingency happens (for example, expensive generation reallocation for a very low probable contingency), whereas curative actions (even if costly) will only be implemented if a contingency happens.

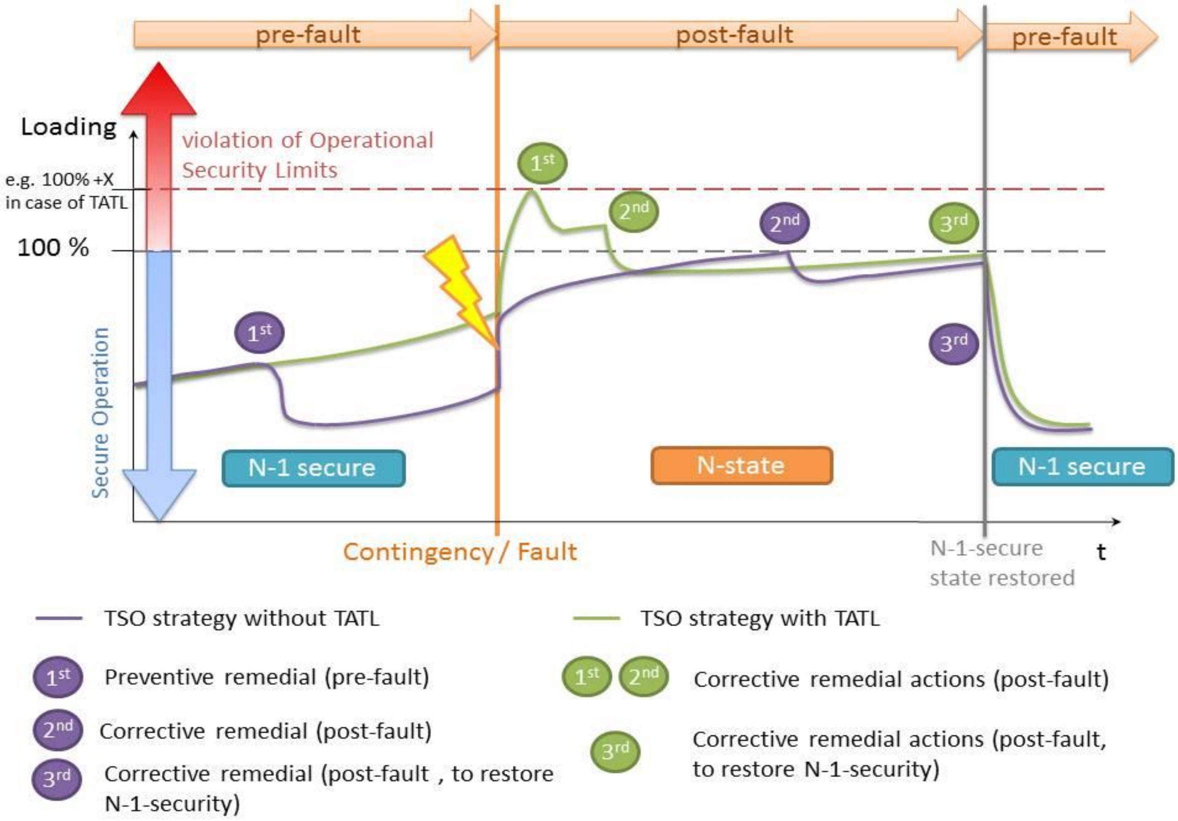

Figure 3 – Possible operational strategies (from iTesla and Umbrella project report [1])

Figure 3 (TATL means Temporary Admissible Transmission Loading) shows how different TSO strategies regarding current limits lead to different operation strategies. This has to be modelled adequately in order to achieve reasonable calculation results.

Some of the above actions are done with the cooperation of third parties (e.g. load shedding in cooperation with DSO).

It has to be pointed out that some actions require more time for implementation (e.g. starting a nuclear plant versus topological action). Therefore, the closer we get to real time, the smaller is the set of possible actions.

3.2.11 The growing uncertainties

As described in previous chapters, especially renewables introduce a strong element of uncertainty.

This uncertainty increases when the analysis is conducted off line, some hours or days before the event; in this case two approaches are possible:

- Deterministic security analysis with some security margins: representing the best, the intermediate, and the worst case
- Probabilistic security analysis with multiple base case scenarios: calculating the confidence of the result by introducing the confidence into weather conditions, availability of network elements, load profile, etc.

In real time application, the uncertainty is related only to the confidence of estimation criteria (or of punctual measurements) adopted for renewables and to marked side effects on scheduling.

3.2.12 Multi-time frame approach

Under the hypothesis of good availability and quality of data, as described in the previous chapters, we can list different approaches based on the best practice of the current on line DSAs:

- From several months to several years in case of prospective studies related to the insertion of new equipment on the grid such as a new HVDC connection.
- From several months to several days for outage planning and seasonal studies.
- Week ahead
- 1 or 2 days ahead
- Intra day
- Real time

The ideal solution would be to create a continuum between the different timeframes. Knowledge and adapted results obtained from a long term study can be used as an input to a medium term study and results from medium term studies can be used for short term studies and so on.

A synthetic view could be illustrated as follows (Figure 4), being the most “rational” and “ideal” reference architecture approach that fits all the requirements.

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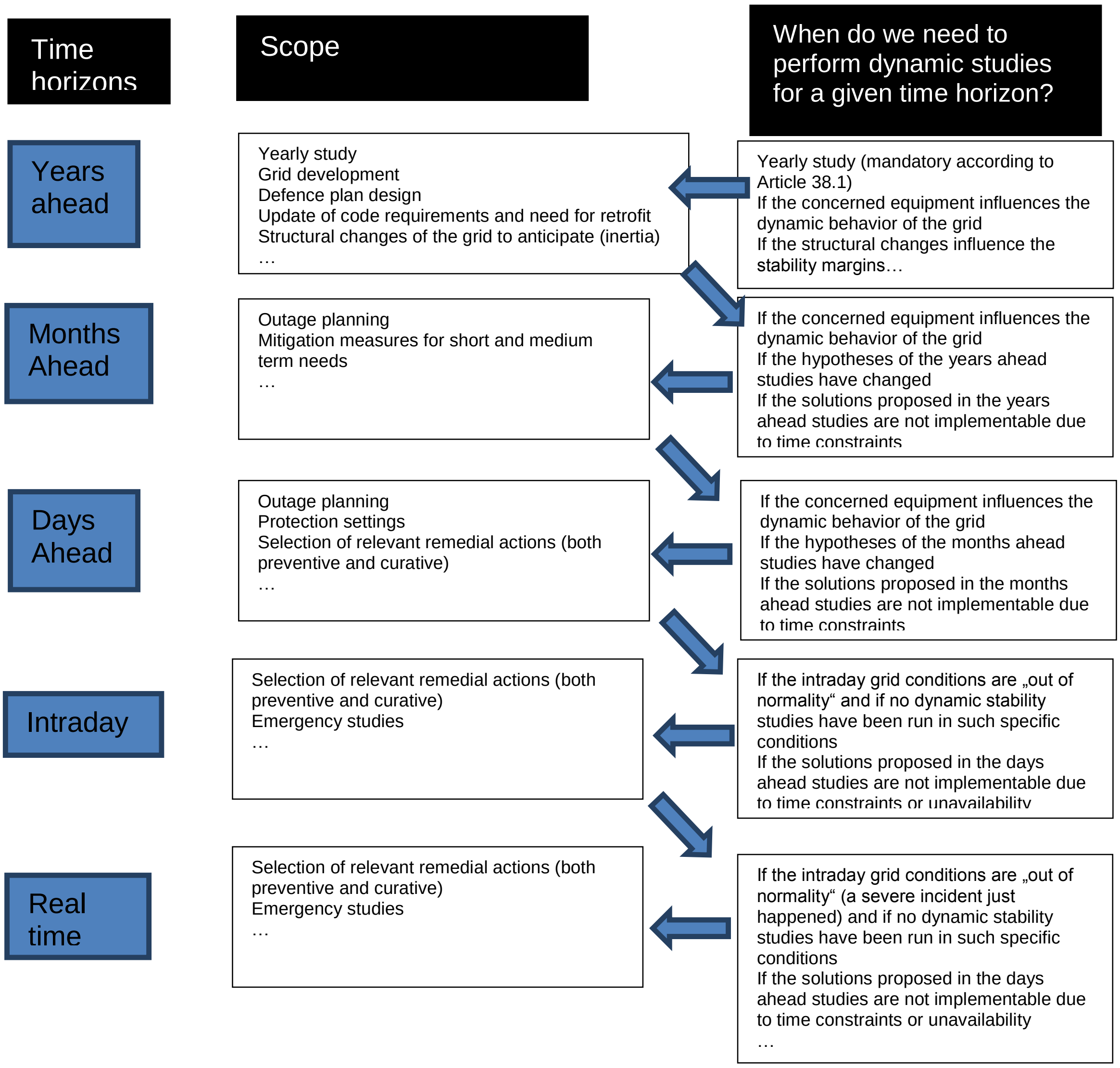

Figure 4 – reference architecture approach (from iTesla and Umbrella project report [1])

3.2.13 Open source languages and modelling methods approach vs "conventional" approach

The aim of this chapter is to compare different strategies to design a DSA system. The first implementations of DSA were based on proprietary tools developed by TSOs.

This approach has the advantage of permitting to optimize the performance of the software using custom models and thus fits the exact needs of TSOs. In some applications all the algorithms are internally developed and maintained.

The system often does not have a standard database or uses files as repository of data.

The real limit of this kind of applications is the interoperability with other software, which is practically zero, and the lack of transparency of the simulation mechanism. The results must be validated and analyzed in order to be considered valid.

In addition, we must consider the risk and economic efforts of developing a customized software.

On the other hand, in the last ten years, with the high diffusion of operating systems well designed to guarantee performances and availability, some commercial software developed for off line application were introduced in real time chains.

The commercial software introduction needs a periodical synchronization of I/O data format and models in order to guarantee interoperability. As for custom software, the results must be validated by comparing with some reference models.

The advantages are evident: in this case, the DSA has the benefits from the experience of commercial development and could be maintained by the provider, minimizing also the necessary economic efforts. The real risk is the availability of the software producer to follow specific TSO needs and ensure a constant alignment to the interoperability prescriptions.

The most flexible approach for DSA design and, in general, for network calculation tools is the opportunity of using open source components. In fact the possibility to know algorithms, models, and architecture in detail, avoids having a black box in terms of calculation results.

The most important advantage of using open source software is that users are not locked in a particular vendor's tool that only works with his other systems. The codes and all implementations are completely transparent: it is possible to modify and adapt open source software for own business requirements, something that is not possible with proprietary systems.

Open source is generally free, for this reason the licensing system is easier to manage, in particular in order to create a common tool for different companies.

It is continually evolving in real time as developers add to it and modify it, which means it can be of better quality and more secure and less prone to bugs than proprietary systems, because it has so many users poring over it and weeding out problems. As for the most important languages and modelling systems for network calculations, consortiums and communities with many experts and developers exist.

To give an example of the most popular open source components in the field of power system calculations, products as QT, C++ for the interface or SQL free databases are very flexible also in terms of experts and developers that could realize a tool.

As for the dynamic simulation, at the moment, a new modelling system that is spreading is MODELICA (https://www.modelica.org/): for this system also a consortium exists that includes Universities, Vendors, TSOs, etc.

4. Calculation Approaches

4.1 Steady-state calculation

4.1.1 Proposed requirements related to the data format:

The requirements are copied from [1] where TSOs involved in both iTesla and Umbrella projects have reached a consensus regarding the needed data format. We recall that both projects aimed at prototyping what could be the new tools for security assessment, including a probabilistic approach and dynamic stability issues:

"Recommendation 1": Exchange of steady-state data in common grid model exchange standard format.

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European TSOs should exchange stationary data of their respective systems in Common Grid Model Exchange Standard (CGMES) format as soon as possible. Identifiers of network elements should be unique and persistent across the datasets in order to be able to perform an advanced security assessment.

"Recommendation 2": Enhanced data format and network modelling.

When exchanging data using the CGMES format, European TSOs should use persistent identifiers for equipment in order to be able to match them with additional data automatically (e.g. dynamic and economic data). The incorporation of the additional information, like redispatch potential, should be considered in the further development of CGMES. Aggregation of injections (loads and generation units, also RES) should be avoided whenever possible and forbidden for large generation units.

Furthermore, TSOs should seek common understanding and as far as possible harmonization regarding the detail of grid modelling.

4.1.2 Requirement regarding exchange of contingency data and remedial actions for coordinated studies:

"Recommendation 3": Exchange of remedial actions in stationary data.

In addition to stationary data of their respective systems, European TSOs should exchange a list of contingencies to be simulated or the methodology to determine the contingencies as well as a catalogue of relevant remedial actions. Moreover, harmonization of the merit order of remedial actions is needed to be able to get common proposals of remedial actions from the new tools developed by iTesla and UMBRELLA. The exchange format needs to be consistent with the description of the system (use of CGMES with unique and persistent identifiers).

4.1.3 Building a starting point for coordinated studies:

In the last years, TSOs across Europe have been developing and commissioning DSA applications according to their needs.

DSA applications are becoming the key tool for ensuring system security at national level. Therefore, DSA should be kept under the responsibility of TSO. Additionally, it has to be taken into account that:

- DSA requires a deep knowledge of both local and global system problems and characteristics (i.e. the level of modelling includes sometimes crucial parts of the distribution levels).
- DSA processes are done in different time frames (system planning, year ahead, operational planning and real time operation) involving different departments at company level: a better coordination is ensured if DSA is an internal activity of the TSO.
- Preparation of the study scenarios is a significantly more complex activity than in the case of static security studies and it should be closely coordinated in all time frames to ensure the consistency of the results.
- Analysis and interpretation of DSA results and provision of potential remedial actions requires exhaustive specialization and a deeper and more accurate knowledge of the system under study than static security studies.

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- Close to real time DSA studies are being developed step by step at national level, with different approaches due to both the complexity of the process and the particularities of each system; this is the natural way of implementation.

4.2 Dynamic calculation

4.2.1 Requirements related to the quality of dynamic models to be used for dynamic studies:

Document [2] presents the different levels of modelling requirements taking into account the proximity of the concerned equipment to the area of study and the type of stability study. This gives good indications on the validity domain of the used dynamic models.

4.2.2 Proposed requirements related to data exchange for dynamic data in coordination studies:

Similarly to recommendations for static data, [1] also proposes recommendations for dynamic data exchanges:

“Recommendation 4”: Exchange of dynamic data in the future transmission system operation.

European TSOs should exchange dynamic data of their respective systems to be able to run time domain simulations on the whole or parts of the European system in the framework of systematic security assessment of system situations from D-2 to close to real time.

“Recommendation 5”: Recommendation regarding the format of exchange of dynamic data.

In the short term, European TSOs should exchange dynamic data using standard or “user defined” models in the format they use for their internal dynamic studies.

4.2.3 Manual study versus automated process:

Traditionally, dynamic studies are driven by an expert using stand-alone software on one base case. This is mandatory for atypical studies such as:

- Study of complex phenomena
- Building and tuning a dynamic model of the given equipment (insertion of a new HVDC line, specific automation, design of a new controller, etc.)
- Feedback on an unexpected phenomena (such as inter-area oscillations on 1 December 2016)
- when the study tool’s limitations are unsure

However, as the system is operated closer to its limits, static analysis on a large number of contingencies and dynamic studies on a reduced number of contingencies are not sufficient. There is a risk of disregarding unacceptable transient phenomena on many contingencies.

In addition, operators are willing to study a growing number of user cases, such as different forecast scenarios and different values of parameters for dynamic models (for example, load models may vary dramatically) to reduce the probability of occurrence of unexpected phenomena close to real time.

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Finally, checking the efficiency of preventive and curative actions might be complex as the number of combination can be high.

As a consequence, many TSOs have set up workflows in batch mode, allowing to run a large number of calculations. This is feasible using homemade software as well as vendor software as they both allow scripting possibilities.

However, the main difficulty in such automated processes is the interpretation of the results to transfer them to the operators as useful information for a good decision making process. A single time domain simulation might lead to hundreds of megabytes of data. Doing this analysis on a large number of contingencies and several base cases might result in terabytes of data. It is necessary to set up data processing functions to extract the useful information to provide to the operator synthetic rules to define the stability domain. As an example, prototyping such methods was one of the main parts of the European project iTesla: one option was the use of decision trees.

4.2.4 Good practice for coordination studies with partners using different simulation tools

Dynamic phenomena that influence more than one TSO need to be analysed via common approach and mutual verification of results.

The process can be divided in the following steps:

1. **Software models:** align and verify main dynamic models like synchronous machines, loads, motors. Select the dynamic order of synchronous machine and the options (saturation, speed dependence, …)
2. **Software settings:** numeric parameters must be aligned with the integration method, integration steps, tolerances, initial conditions management, and load flow options. **In such situations, simple adoption of same settings could not be sufficient because the software may require a specific implementation.**
3. **Dynamic control models of AVR, prime mover, PSS, transformer/PST controllers, HVDC, wind farms, photovoltaic, etc. and their settings**
4. **Select a proper representation of Dispersed Generation:** depending on studied phenomena, represent controllers, protections, Low Voltage Ride Through (LVRT)curves, etc.
5. **Evaluate whether to represent protections** (distance, generator protections, …) and check whether models and used settings converge
6. **Introduce, if needed, defence plans**: under frequency load shedding, Special Protection Schemes …
7. **Validation in small reference system**: each object described in the previous steps must be validated by comparing results, state variables, etc. in a “small controlled reference system”, for instance by studying the step response.
8. **Define the boundary of electrical area which is the object of the study and the system equivalents to be represented outside this area**.
9. **Validation on electrical area which is the object of the study**: evaluate, selecting some significant objects (synchronous machines, loads, nodes, etc.) for test purposes and compare the results.

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The previous suggested rules are the precondition to execute coordinated studies, but what needs to be done in parallel, to manage this activity in efficient way, is to try to drive the commercial software in the direction of complete interoperability in terms of I/O data.

For commercial software this is an important issue in order to guarantee clear and transparent use of different vendors' software by TSOs.

On the other hand, it is important to have an agreed approach on the phenomena to be studied (refer to figure 2) to avoid unnecessary excess of detail in representation of the system, that can generate numeric instability and false results due to uncertainty of several parameters.

The reported points 1…9 were the steps applied by SPD group during defining the "initial model" reported in [3], in which, after selection of real transients documented by some WAMS recordings, different simulation tools were aligned in order to converge on the real system behavior.

4.2.5 Improving the quality of dynamic models

One possible path is the software to software cross validation: this can be done by comparing the simulation outputs of different tools and trying to explain the differences (if any). It is one of SPD group's missions to build a reference library of standard models.

This cross validation can also be done by comparing the simulation results of a high fidelity simulation tool using a detailed model, which is supposed to be the reference. This way, approximate phasor models can be compared with EMT models.

In the case no reference model is available, timely high-resolution measurements records can be used instead as presented in the next chapter.

4.3 WAMS and DSA:

4.3.1 Use of WAMS for online monitoring:

In most recent applications the dynamic assessment of grid is managed with support of external systems; in detail, some calculations can be performed by the help of phasor measurements from WAMS.

Different approaches are currently under study over the world:

- Use of WAMS in order to perform "fast SCADA" calculations derived from a hybrid status estimator (WAMS phasor measurements enable running a fast state estimation, very precise in terms of voltage angle difference and synchronization)
- On line voltage stability or transient stability margins evaluation
- Security evaluation of voltage angle differences over the system
- MLE (Maximum Likelihood Estimation) techniques, which mean using "learning systems" that withdraw DSA results and construct a simplified model coupled in real time with WAMS
- Modal analysis tools like Kalman, Prony, Wavelets, PCA (Principal Component Analysis), etc.

At present, a complete integration between WAMS and DSA worlds does not exist, but there is a clear trend towards of their deeper integration in a general security evaluation system.

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4.3.2 Model validation and parameter estimation using PMUs recordings:

A given model is not a true and unique description of an actual power system. A “good” model only represents a suitable description of the system for particular aspects of interest. In this context, power system models should be able to describe dynamic phenomena or stability cases such as those exhibiting small signals as well as frequency, voltage and transient dynamics.

Model validation can therefore give a good confidence of the fidelity of the models for replicating dynamic phenomena.

This can be done by reproducing past events with dynamic simulation tools and by trying to adapt the models and parameters to get simulation curves matching real event records.

The process can be summarized by the Figure 5.

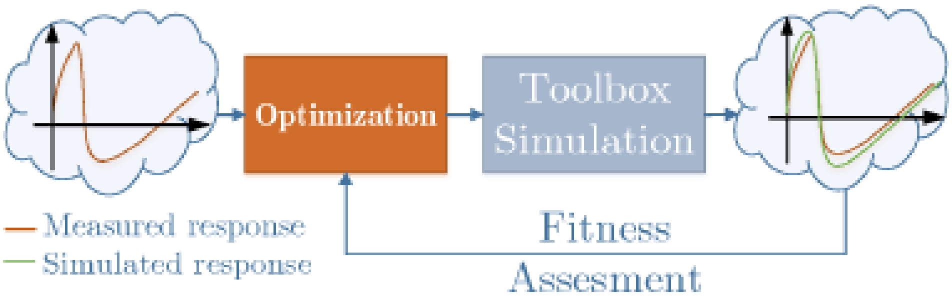

Figure 5 – Working principle of RaPId (KTH University software for model validation)

However, it is of crucial importance to have within the toolbox the most appropriate structure of the internal process as otherwise the validation process will not converge.

In order to set up this process, critical points have to be addressed:

- The ability to reproduce the scenario with the correct pre-event conditions
- The selection of appropriate models to have a good parameter identification of the model
- The selection of a good criterion fit

4.4 Protection Devices involvement

Since transient stability and dynamic studies are concerned with the ability of the power system to maintain synchronism when it faces severe disturbances, a satisfactory performance of certain protection systems is of great importance in ensuring system stability. Protections must be able to distinguish among faults, stable power swings, and out-of-set conditions. They initiate circuit-breaker operations to clear the faulted elements. In addition, they must ensure that there are no further operations of relays causing unnecessary opening of elements during stable phenomena, and also that they do not fail to operate when they should. If the system is unstable, we need to know how it separates, in order not to propagate the disturbance, and whether the point of separation is acceptable.

Consequently, the evaluation of the performance of protection systems during the transient period, particularly the performance of relays used for protection of transmission lines and generators, is of major importance.

Hence, protection devices and their appropriate modelling strongly affect the quality of the results in real time applications.

Figure 6 shows the Protection simulation model inserted into a DSA tool (e.g. Power System Simulator).

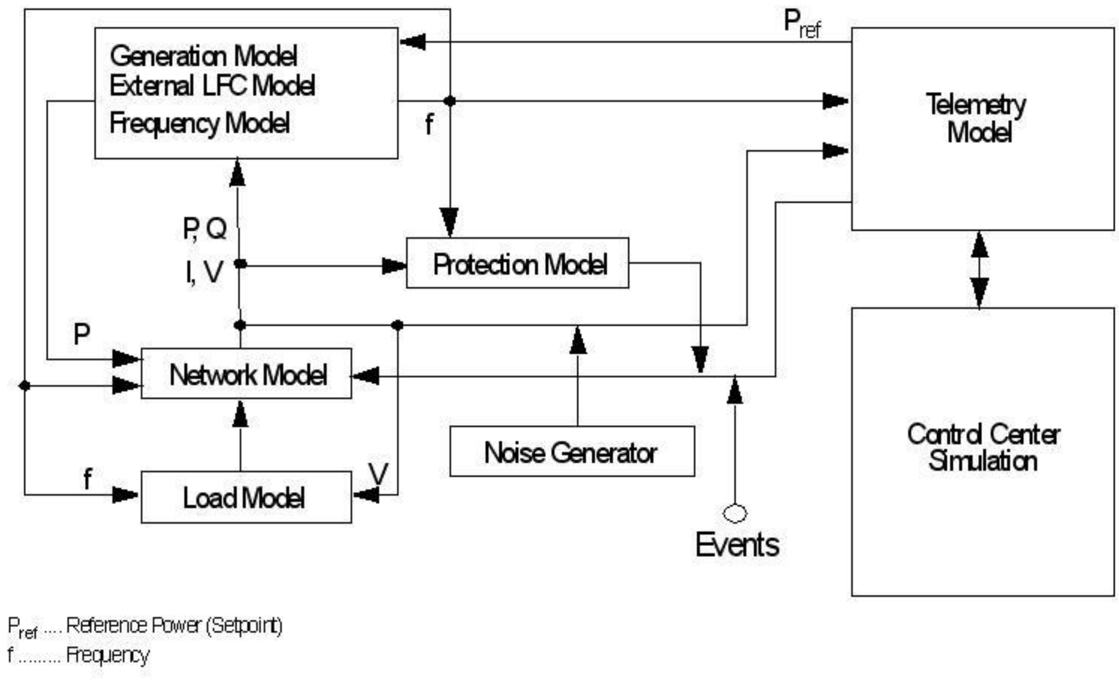

Figure 6 – Protection simulation inserted into a generic DSA tool

Depending on the software platform, there are various methodologies.

4.4.1 Protection models manually embedded in the DSA tool

The protections are considered in the DSA tool as simply opened due to relays' energization and tripping.

4.4.2 Protection models embedded in the DSA tool

The protection model in the DSA tool may consist of two parts: Relay Models and Logical Combinations.

A normal sequence of events for the protection system may be split up into the following steps: Recognition of a fault condition > automatic protection actions > disappearance of the fault condition.

At any of these stages there may be associated signalling messages generated by the relay. Due to these facts, the relay actions are modelled by defining the fault condition and corresponding relay related action sequences (sequence of events) for the different stages.

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If a fault condition is detected, the recognition signalling (pickup) sequence is executed at once. Afterwards, the protective action (operation) sequence is triggered; possibly after a time delay, depending on the relay characteristics. If the fault remains until the time delay has expired, the sequence is executed. Otherwise, the disappearance signalling sequence is executed when the disappearance of the fault condition is detected.

I the following, a typical protection scheme for a DSA tool is given (e.g. distance relays: Zone 1, instantaneous at the 80% of the Line, Zone 2, 64% of the shortest next Line, t2= 0.4 sec, etc.) , relays are created (via user friendly commands) in the appropriate locations. Afterwards, it is possible to make manual adaptations to the relays.

Relays that are modelled are: Over/Under-frequency Relays, Over-current Relay, Over/Under-voltage Relay, Transfer Trip Relay (Transfer trip relay operation occurs only in consequence of other relaying actions (usually over-current or distance protection), Busbar Protection, Breaker Failure, **Transformer Differential**, Auto Recloser, **Synchronism Check**, and Time Controlled Switched Relays.

4.4.3 Impedance (Distance) Protection

After selection of a fault (3-phase) at the desired location (line or busbar; faults on transformers are shifted to the nearest busbar), DSA tool starts a short circuit calculation. Depending on the impedance and characteristic of the relays, the activation and operational messages are performed. Then, with the new network situation, the short circuit calculation is started again and the relays are checked against their limit blinders. The loop "short circuit calculation – relay" is carried out until the fault is isolated or none of the relays detects the fault anymore.

The detection of a fault is performed if the impedance reaches the area marked with 'detection'. As example, various quadrilateral relay zone characteristics are shown in Figure 7.

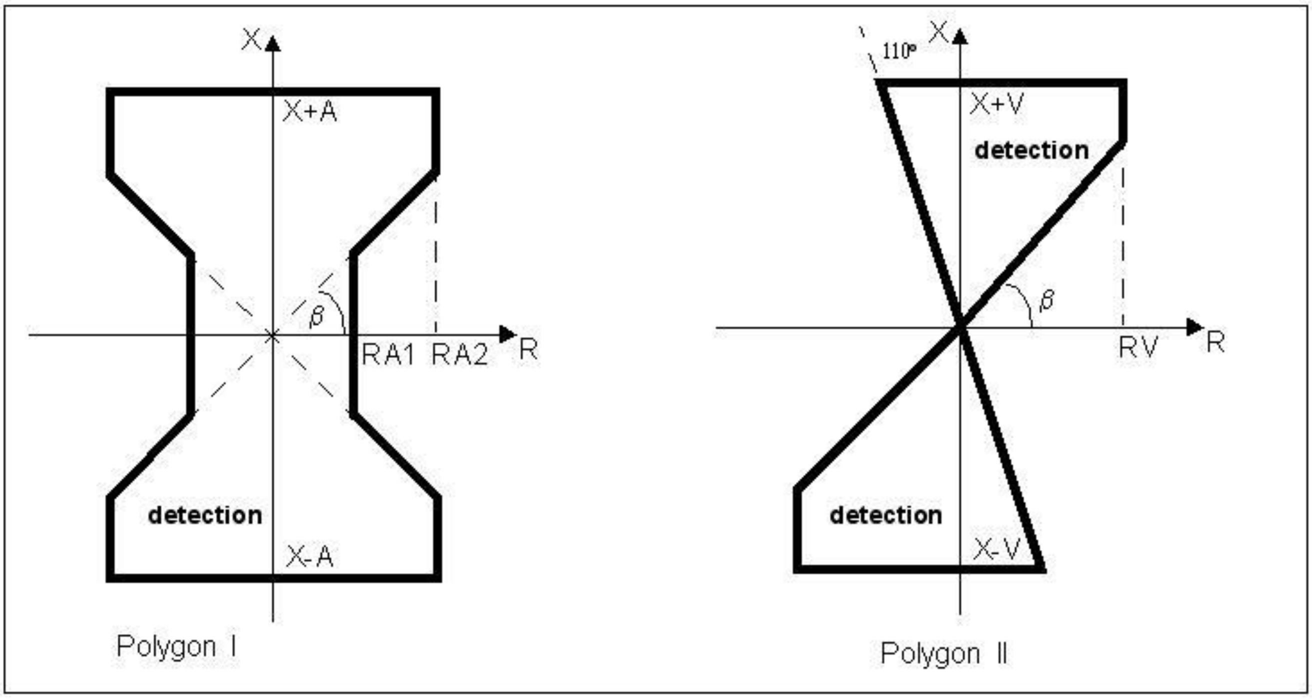

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Figure 7 – zone characteristic

In detail:

- R, X active and reactive part of the impedance, RA1
- RA2, X+A, X-A, parameter for polygon I
- RV, X+A, X-A, parameter for polygon II

If all conditions are met, the relay operates after the predefined time delay.. If the fault has already been isolated by other relays, the relay is reset.
A short circuit is defined via an event. Events can be defined as a single event or in an event sequence.
The parameters for an event are:

- **fault location** (definition of a busbar, transformer or a line; for a line, the location must be defined by a percent value (distance) from the start node),
- **fault type** (3 phase fault, etc.),
- **fault duration** (the fault duration is permanent; every time the faulted network component is set under voltage, the relay triggering is activated),
- **arc** (the fault is active only for a short time; the event has no effect if the network component is not under voltage; if the component is under voltage, the relays isolate the fault; afterwards, it is possible to resupply the network component),
- **no short circuit** (this option serves to remove a permanent short circuit).

4.4.4 Protection models integrated at interlinked with the DSA tool

For protection engineers, simulation tools exist that give them the ability, among others, to design and evaluate the fast, wide area control needed to avoid cascading outages and blackouts. The next generation of such type of commercial programs integrate a protection simulation program with conventional transient stability programs using convenient control and communication models. To ensure the reliable operation of the electric grid when subject to disturbances, tools for design and analysis of wide area control and protection algorithms are needed, which use sensor inputs not just locally, like conventional protective relays do, but from multiple locations in the network.

It is difficult to model thousands of local protection relays in a typical transient stability program. Often a stability study reflects only the action of a few selected relays, and sometimes only manually. On the other hand, the typical software to study protection systems can model thousands of relays, but it cannot model the dynamic behaviour of the power system.

The interdependence of system dynamics and relay actions must be captured if cascading failures are to be accurately predicted and studied. Moreover, the increasing use of special protection schemes and wide area controls presumes that the available analytical tools are able to adequately model them. Modern S/W tools bring these two approaches together. The procedure is as it follows:

DSA S/W provides the dynamically changing voltages to the Protection Simulation S/W (PSSW) at each time step.

The Protection Simulation S/W model contains detailed knowledge of the protection system. It calculates branch currents using the previous voltages and PSSW's own zero and negative sequence impedances, and evaluates relay operation. If breakers operate, that information is passed onto DSA S/W in the corresponding time step.

The calculation proceeds until the simulation time elapses or the user decides to halt the simulations.

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It creates time varying plots of magnitudes of voltages and voltage angles, frequency, relay apparent impedance, generator rotor angles, etc. It allows the study of different contingencies and scenarios, some of which may lead to cascading outages, while others may not.

5. Results and Human Machine Interface (HMI)

This section resumes the technical recommendations about Human Machine Interface. In fact, the real goal of DSA is to translate complex and specialist evaluations in:

- Clear and simple information
- Suggestions for actions over the system

The first approach could be geographical; nowadays, with powerful GPS geographic localization, it is very easy to show a schematic view of the system superimposed over geographical maps. This is a very powerful overview of the system. In such applications, in addition, coloured heat maps are very efficient to give a fast feedback about voltage profile or angle difference over the system.

Sometimes, the way to navigate is hierarchical, i.e. pointing the cursor to a line or a substation is possible to visualize the substation scheme with indications.

Another efficient technique of visualization is tabular with list of contingencies and main results, additionally correlated with traffic lights that give immediate feeling of severity of a contingency.

Also, tabular approach is suggested that gives a possible navigation criteria with increasing the complexity of information step by step. This means that a single contingency could be more deeply investigated making available more pages with more complex information and graphical trends.

Part of HMI is the judgement of contingencies treated in previous chapters.

It must be underlined that the operator role is not only passive, but could be more active, being able, trough the HMI, to create new study cases or contingency list. The main suggestion is to make available some "default" pre-defined contingency as, for example, busbar faults, short circuit on lines, or generator trips. The predefinition is important because the expert engineer who configures DSA's default cases well knows the right sequence of events, the time duration, and the typical behaviour of the protection. Therefore, the user can be sensitized by customized pre-defined faults.

This will be certainly an added value giving to the TSO a higher perspective over the system.

6. References

[1] Umbrella and iTesla projects: common deliverable D8.4/6.3 "Common recommendations to ENTSO-E regarding TSO & RSCI rules for business processes and data exchange"

[3] https://www.entsoe.eu/publications/system-operations-reports/continental-europe/Initial-Dynamic-Model/Pages/default.aspx

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