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Comprehensive approach of power system contingency analysis

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***Abstract*—Security of supply in power system supposes that the robustness of the system can be guaranteed in case of credible contingencies. This robustness relies on structural redundancy and on security margins. Traditionally, the "N-1" contingency analysis has been used for such check. This methodology leads to the definition of "sizing incidents", or credible contingencies[1]. The system is said "N-1" secure if it remains within its operating domain for these "sizing incidents". Today some trends exist for relaxing the application of this criterion. This means that some emergency control actions must be implemented in the system for guaranteeing its security. This asks for their representation in the methodological approach used for evaluating the security of supply. This is not possible with traditional tools.**

***Index Terms*—Interconnected power system, industrial power system, load flow analysis, power generation control, reactive power control, voltage control, power system dynamic stability, power system transient stability, static VAR compensator.**

I. INTRODUCTION

THE continuity of service in developed system is certainly the main concern of system operators. For reaching high level performances, electric sector had, until recently, all necessary means at disposal: rigorous planning of the development of the system, integrated management of generation and transmission, investment capacities in concordance with technical objectives agreed between the different components of the society. This favorable situation permitted to maintain power system operation at sufficient distances from its physical limits, with few concerns about what could happen if such limits were overtaken. Very deep incidents, quite rare, revealed often some risks attached to particular deterioration mechanisms, which were previously completely ignored by operators.

Power system unbundling is progressively modifying the conditions for such controlled management of power system security. Indeed, the free access to the interconnected system, bilateral contracts settled between generating companies and consumers make conditions of operation more and more unforeseeable. The quest for the maximum economical efficacy leads to the use of interconnection capacities far above levels expected when they were built.

All these changes lead to the operation of the system nearer to their physical or to their stability limits; this increases the risk of transgression of these limits in case of emergencies. It is thus necessary to know more precisely these limits and to better understand what could happen beyond them, such that adequate countermeasures and systemic protective schemes can be developed [2] - [3], [6], [8]. All these means should permit, if such incidents do occur, to contain them and to avoid complete or partial collapse of the system.

The role of system modeling and of simulation tools cannot be overestimated for the acquisition of a clear knowledge and a deep understanding of these phenomena. Looking to real cases remains naturally an incomplete and unsatisfactory approach.

The dynamic model of the system, real encyclopedia of the modeling of system components, becomes itself the main source of the knowledge of the systemic behaviors.

II. PREVENTIVE SECURITY MARGINS

Continuity of service in case of contingency affecting the system can only be guaranteed if certain conditions are fulfilled in terms of system structure on the one hand, and in terms of organization of the system on the other.

The transmission system is based on a meshed structure allowing for reaching each substation by at least two different ways. Further, specific methodologies are used during the development studies of system infrastructures, procedures are used in operation, such that some margins are left, which are necessary in case of contingencies.

These methodologies and procedures are checking if contingencies and normative incidents will not drive the system operating state beyond certain limits, keeping "sufficient" margin against system collapse. These limits are set up based on system operator's experience. They are often revisited and modified after some critical incidents have provoked a collapse.

Keeping margins supposes a certain overinvestment in generation and transmission, but also not optimal operation of the system. This preventive security has a price. The definition of criteria for the development and the operation of the system, in the meaning used in the present paper, that is to say contingencies for which the system must stay in its operating area, may be important in terms of additional costs for

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covering indistinctly events of significantly different probabilities.

At least at planning stage, probabilistic approaches are presently recommended. They tend to accept risks whose probability of occurrence is sufficiently low. This consequently supposes that specific procedures or defense countermeasures have been adequately prepared (this supposes studies) and suitably implemented (this means site deployment if it is deemed necessary), the preventive security being not there anymore for guaranteeing the robustness of the system against these specific contingencies.

Amongst deterministic security criteria, the most generally used is certainly the “N-1” criterion. Indeed it corresponds to possible events. This criterion stipulates amongst other things that in its state “N”, that is to say when all elements of the system are in operation, operating conditions are in accordance with rules. Generally this is tested for different conventional states: at least for peak and off-peak load of the system, etc. It implies further that for all types of incidents leading to the disconnection of only one element (generator, circuit, line, transformer, etc.), the system operating point stays within the requested area. The operating point and the system is then declared “N-1” secure.

This approach is often “generalized” considering, at least for some devices, the loss of more than one element, turning the criterion from “N-1” to “N-2”, to “N-x”. In these cases, the system operating area is generally enlarged, considering some overload capabilities of system elements.

When “x”, the number of lost elements, is getting higher, the state of the system can be driven far away from its normal acceptable conditions. The unfolding of such incidents leads to operation of emergency controls, which can represent a difficult undertaking for traditional contingency analysis methodology.

III. THE CLASSICAL APPROACH

The “N-1” criterion is an “abstraction” representing equivalently a single contingency (element kept out of service for maintenance, generating unit not scheduled, etc.), or the tripping of one element following a normative incident, like a three phase short circuit.

The classical approach supposes that a load flow is used for the contingency analysis, suitably tuned for taking account of the specificities of the system under consideration. The fact that an element is out of service for maintenance or tripped following an incident is generally treated equivalently. For the most critical cases in depth investigations must be made using more precise tools, amongst others transient stability programs.

Even if a probabilistic approach has been adopted for checking the development of a power system, its operation supposes the definition of “sizing incidents” corresponding to “credible contingencies”. Such definition is generally not independent of the system which is considered. Usual options, for incidents, are as follows:

- For powerful and well meshed systems, three phase fault cleared by the first stage of protective scheme or possibly by the backup protection for the most robust of them;
- For weaker systems, or for weaker part of systems, two phase fault or even single phase fault cleared by main protection, with auto-reclosing;
- For particular conditions, systems are not able to support faults, but simply loss of elements.

In all of these cases, a preventive security margin must exist against these chosen normative events, if one expects that a post fault stable state exists.

IV. PRESENT EVOLUTION

A. The classical approach is not always satisfactory

For technical and economical reasons the system can be more stressed then it should be for a secure operation. Some investments cannot be justified (geographical conditions and weak load density), or the system development cannot follow the pace of consumption increase (sudden and fast increase of the consumption and insufficient resources for investment), or the high peak to off-peak load ratio leads to operation characterized by very high loading during daily of yearly peak period, etc.

The effective conditions of system operation, its loading, the type of load, do not allow the straightforward application of traditional methodologies. These groundless generalizations without considering adequately the system specificities can lead to unexpected system failures.

Present conditions of unbundling lead progressively to some degradation of the security margins of large and developed systems. Some actors in the market consider that the system, while respecting the criterion, is operated too uneconomically. Then taking account of the very low probability of occurrence of these “marginal” incidents, they come to the decision of operating the system without respecting the criterion in these cases.

The difficulty of transmission line construction led to the introduction of power electronics in power systems. This is attractive because it permits fast as well as steady state control. This allows for alleviating some classes of problems, but simultaneously the system is made more fragile during emergency regimes. Indeed power electronic is characterized by its limited overload capabilities as compared to classical hardware. Moreover changes of control structure and operation of these devices are also taking place during system incidents, for example during severe voltages dips.

These last considerations resulted from the ever more present “active” system security that tends to replace the passive approach, holding on preventive security, which was recommended earlier. Incidentally, during the same period of time, the design of the Nuclear Power Plant of the future switched from an active to a passive implementation of cooling in emergency conditions. This shall permit the plant to stop quietly in absence of AC electrical supply.

B. Consequences

As a consequence of this evolution, preventive security margins do not exist systematically. Hence thermal overload or loss of steady state, transient or voltage stability can take place for some of the credible contingencies.

Thermal overload for classical system components are generally characterized by sufficiently long time constants to permit reaction of the system operator. Generally such overload capabilities are taken into account in the planning methodology and accepted for the most critical incidents. In particular transformers can sustain significant overload for a long duration "just" at a price of an accelerated ageing.

If, for certain of the credible contingencies, risks of loss of steady-state or transient stability exist, automatic countermeasures should have been developed and included in the overall process. These countermeasures, which normally are implemented in defense plans, constitute here an integral part of the system security of operation. As such they must be considered in system studies, the faster the degradation process, the more important their detailed representation within study tools.

V. DYNAMIC SECURITY ASSESSMENT TOOL: SYSCAN

Initially developed for on-line application, SYSCAN (System Collapse Analysis) was built for the determination of operational margins against (voltage) system collapse. The determination of these margins asked for setting the system in stressed conditions starting from actual operating points [4]. This was implemented using different kind of load increase.

The use of SYSCAN has been widened. It consists in automating the execution and the analysis of dynamic simulations in order to allow an exhaustive approach of the study of system security. The methodological approach considers the system subject to a large number of possible operation modes, in order to identify its weak, critical or vulnerable elements.

The software is based on a detailed modelling of the system and an intensive use of simulations. These simulations are performed using EUROSTAG®, software tool for dynamic, transient and long-term stability analysis. This new method for the determination of the operating limits gives SYSCAN an accuracy which is significantly higher than traditional procedures, relying on steady state analysis, when these latter are possible.

Therefore, SYSCAN can claim the status of a universal DSA (Dynamic Security Assessment) tool, able to analyse risks of outages of all types: voltage collapse, loss of synchronism, frequency collapse, etc., under specified conditions.

Starting from an initial steady state, the system is subsequently put under stress. The way it is performed must be consistent with the aim of the computation and the state of the system which is considered. The stress is applied by means of a list of events affecting the system operation.

Those stress events can be: area, machine or model set-point modification, area or single bus load modification, time load evolution, machine switch-on or switch-off, etc., even equipment nominal power adjustment.

Once the system is put under stress, a list of incidents is applied. These incidents can be generic or individual. An individual incident can be a single event or either a group of events. Those events can be: opening or closing of a line, setting of short circuit at a node or on a line, the elimination of short circuit at a node or on a line, a machine start up or shut down, a compensation bank modification, etc.

SYSCAN determines an operational limit or a stability margin, based on pre-defined criteria determined at each step of the integration process, or based on user-defined criteria based on mathematical formulae, which are evaluated by the tabular output program of EUROSTAG. Alarms can also be evaluated using the same means.

As SYSCAN uses the EUROSTAG integration algorithm, based on a variable step size, it allows for controlling the calculation accuracy while preserving acceptable execution speed. The system under maximum stress is initially evaluated. Subsequently, if some incidents are refused at the maximum stress, some intermediate states are checked. A dichotomic search approach allows accelerating the determination of the stability limits, minimising the number of stress levels at which the incidents have to be evaluated (this represents normally the bulk of the work).

The search algorithm evaluates first the incidents at the system maximum stress. If some incidents are refused at this stress level, the stress is reduced down to 50% of the maximum. If all the incidents are accepted at this stress level, the stress is increased up to 75%, and if some of them are refused, it is decreased again down to 25%. The algorithm continues until the specified accuracy is reached. Accuracy is reached when the algorithm has identified two consecutive stresses whose stress level difference is lower than the required accuracy: no incident has been refused for the first stress level, and at least one incident has been refused for the second stress level.

If an incident is refused at a given stress level, it has to be checked again for the next tested stress level, whatever it is higher or lower. If an incident is accepted at a given stress level, it has to be checked for the next tested stress level only if this stress level will be higher. In other words, this incident is assumed to be accepted for all the lower stress levels. That's why the program stops if all incidents are accepted at the maximum stress level.

The summary of the results shows the most dangerous incidents, which are those with the smallest stability margin. This corresponds for instance to the highest stress level that the system can undergo without compromising the incident-based security rules (defined by the user).

Further analysis is possible to confirm the diagnostic. The EUROSTAG analysis tools like time-domain curve display, tabular output, or one-line diagram result display are available for analysing the significant simulations that have been performed during each SYSCAN session.

SYSCAN, further to the exhaustive analysis of system security, can be used for the development of adequate countermeasures guaranteeing system security of operation. It also allows for evaluating in detail the performance of such countermeasures facing different system conditions, as it will be illustrated with the next examples.

VI. EXAMPLES

A. Case study 1

This first example illustrates the use of SYSCAN for optimal location and size determination of SVS.

1) Generals

When a significant part (up to 80%) of the load is made of air conditioner (AC), the load modeling becomes essential in system studies. Additionally, the short duration of peak provokes operations at very high loading during these periods. In case of fault, even normally cleared in base time by the protective gear, the induction motors of the AC window units stall. Low voltages, slow voltage recovery and high currents resulted in the system. The main driving factor of the stalling phenomenon is related to the voltage drop in highly loaded transformers. In absence of corrective measures, namely the activation of a dedicated under voltage load shedding plan, this phenomenon can propagate to significant portions of the system, threatening its security of supply.

2) Phenomena description

The stalling of the induction motors leads to high currents and higher voltage drops, which can provoke the blocking of other motors. The phenomenon can extend to neighboring substations. It corresponds to a fast voltage collapse in the MV and distribution systems although the “classical” transient stability related to generators is verified.

The distribution, transmission and generation parts of system are affected in manners which are described hereafter by increasing order of severity:

- Delayed and slow recovery of the voltage with sustained HV voltage comprised between 0.75 and 0.9 p.u. The slow voltage recovery results after a few seconds from the activation of the thermal relays of AC unit.
- When present, activation of the implemented under voltage load shedding protective scheme. When the amount of shed load is sufficient, a voltage recovery takes place rapidly, but at the expense of customer’s interruption. The sudden unloading of the system may trigger over-voltages forcing the automatic insertion of shunt reactors.
- When the UVLS is absent or insufficient, the high currents incurred in the MV and transmission systems can lead to back up over current or stage 3 distance protection activation threatening the integrity of the transmission system.
- On the generation side, the delayed voltage recovery provokes large generator currents with risk of generator tripping by their stator over current protection.
- Additionally, the presence of sustained low voltages in the transmission system could trigger transient stability problems like inter-area oscillation etc.

3) Impact of SVS on slow voltage recovery

Due to their excitation time constants, particularly when brushless exciter is used, generators reaction is too slow to block the induction motors stalling process that takes place within a one second time frame. Thanks its fast dynamics, SVS can supply additional reactive power reserves and is an efficient countermeasure to avoid the activation of the under voltage load shedding in case of “normal” disturbances.

4) System description

The system is composed of 5 major areas: 3 large urban load centers and two large generation centers, all interconnected in 380 kV. Each load center has its local generation. Transmission system in each center is made of “islands” supplied through 380 kV step-down transformers.

The resulting model is composed of 800 buses, 1200 branches, 127 generators and 280 induction motors.

5) Load modeling

The AC load is connected in low voltage (0.4 kV) downstream three voltage transformations (380/110 kV, 110/13.8 kV and 13.8/0.4 kV). In peak load conditions, transformers are highly loaded with a mean loading of the 110/13.8 kV transformers above 80 %. The ad hoc representation of the load behavior is of major importance as it is the main cause of the motor stalling and voltage instability phenomena.

Therefore, the 110/13.8 kV transformers are represented and the motor load (75% of the total) is connected to the 13.8 kV voltage level. The 13.8/0.4 kV transformer impedance and the MV and LV impedance of feeders are added to the stator impedance of the motor model. The load presents a linear torque speed characteristics.

6) SVS sizing procedure

At the planning stage, the main task consists of the optimal location and sizing of the SVS to be inserted in the system. The main steps of this location and sizing process can be formulated as follows:

- Definition of a set of sizing disturbances: in the present case the set of sizing disturbance will be “single” fault cleared in base time without subsequent auto-reclosing, set at all possible locations of the transmission system.
- Definition of an acceptance criterion: an SVS sizing will be considered acceptable if, in post fault conditions, the following conditions are verified in the large consumption load centers: a) no motor stalling, b) sufficient voltage recovery to avoid the activation of the under voltage load shedding relays and c) complete recovery of the SVS terminal voltage within 1 s after the fault clearing.
- Setting of an arbitrary large SVS in each important substation and simulation of all the sizing contingencies. These are the faults affecting the 380/110 kV transformers and the main corridor supplying the large load centers. Though a heuristic choice is performed, the locations correspond to the secondary side of the main HV transformers injectors.

- Definition of a stress: in the present stage, the stress corresponds to the reduction of the SVS ratings for given system loading condition.
- Determination of the maximum acceptable stress that can be withstood by the system while the acceptance criteria are verified for the entire set of contingencies.
- Optimization of the SVS design is made in terms of composition (BSC, TSC, and SVC) and layout (space requirement, availability etc.).

TABLE 1
SVS SIZE IN FUNCTION OF LOCATION, TYPE OF FAULT AND LOST ELEMENT (LINE, CABLE OR TRANFORMER)

SVS Locations	3 Ph. Faults	1Ph.Faults on L & C	1Ph. Faults on T
SVS 1.1	500	150	350
SVS 1.2	750	300	550
SVS 1.3	500	200	250
SVS 1.4	750	200	350
SVS 1.5	560	200	300
SVS 2.1	675	300	300
SVS 2.2	450	200	200
SVS 3.1	250	-	-
SVS 3.2	310	-	-
SVS 1.6	375	-	-
SVS 3.3	125	-	-

7) SYSCAN simulations and SVS sizing results

The set of contingencies consist of three phase faults and single phase faults on all overhead lines, cables and transformers of the transmission system with loss of the faulty element.

Constant clearing times of 5 and 7 cycles are assumed respectively for the 380 and 110 kV voltage levels. The operating point corresponds to the hot summer peak load conditions expected for the year when the SVS will be put into service.

Initial sizing of SVS shows that with 12 SVS rated at 700 MVA each and having a range of 95% capacitive and 5% inductive, the voltage stability is achieved for all the considered contingencies. This sizing will be considered as the 0% stress situation. The situation where no SVS are installed is considered as the 100% stress situation.

Preliminary SYSCAN runs verify that the stability criteria are satisfied at 0% stress and are violated at 100% stress; the largest stress has to be interpreted as a size reduction. The table 1 presents, for the various locations, the stress that can be applied to the SVS size to achieve the voltage stability of the system. The SVS sizes have been rounded at the 50 Mvar higher figures. The results show that:

- Most severe contingencies are the three phase faults affecting the 380/110 kV transformers on the 380 kV side;
- The most requested SVS's are characterized by the largest sizes (load center 1);
- Should the motor stalling phenomena be avoided following 3 phase faults, the total SVS rating required should be exaggeratedly high.
- Each SVS size is characterized by a subset of critical contingencies.

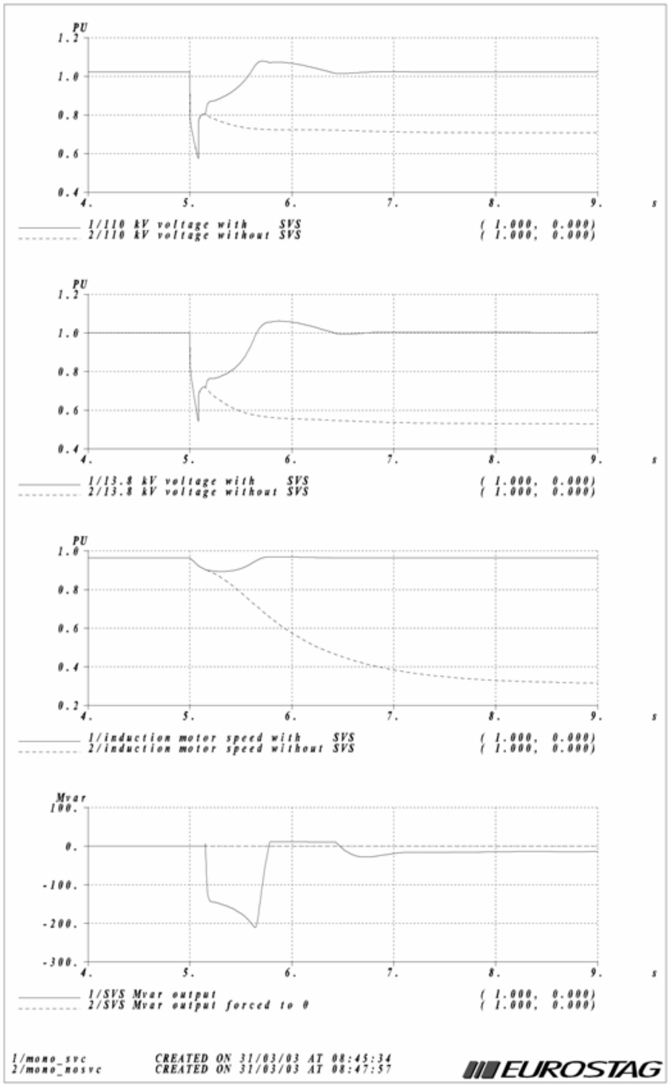

Figure 1 - System response to a 5 cycles single phase fault on a double circuit line connecting the generation center and the main load center (labeled 1).

As a consequence, considering that three phase faults are rare, it has been decided to determine the SVS ratings for single phase faults. Three phase faults and other more severe contingencies should be covered with the under voltage load shedding scheme included in the defense plan.

Figure 1, graphs 1 to 4, displays the system behavior with and without the presence of SVS for a 5 cycle single phase fault on the double circuit line connecting generation center and the main load center (labeled 1); graph 1 and graph 2 show the voltage behavior at the 110 and 13.8 kV levels. The impact of the SVS on the induction motor speed and stalling process is shown on graph 3. The SVS reactive power output is displayed on graph 4 (positive while inductive).

B. Case study 2

Case 2 concerns a weak system in an emerging country, where the limited investment resources and the high developing rate of the consumption do not permit an adequate level of security of operation. The set up of a rational approach asks for the ranking of the different investments in terms of their potentiality for a global better quality of supply.

The system structure, its weakness, the type of load do not permit to use "traditional approaches", based on load flow analysis, as a great number of the incidents are leading to abnormal operating conditions. In particular numbers of contingencies are leading to partial system collapse, which should be tackled by emergency control countermeasures.

The first task consisted of the development of a dynamic modeling of the system, based on the concept of "extended electromechanical modeling", core of typical EUROSTAG approach. This allowed for a comprehensive approach of the system security, for different time horizons.

The proposed ranking was essentially based on technical analysis and, at least during this first stage of the study, did not take account other considerations like economical, strategic or political specific interests. This has been implemented by the final beneficiary of the study.

The developed methodology led to the detailed screening of the different additional network investment while checking the "position" against the full list of system operating criteria. The list of single contingencies (this means sudden loss of the element following or not a single phase fault) and the total number of planned elements led to a large set of simulations of the order of 5 000.

Initial system conditions, for all situations which have been studied, have been OPF optimized, using the maximization of reactive reserves principle [5], [7]. This allows for the best mutual support of reactive power sources, and it leads to a clear situation with well distributed reserves which can be straightforwardly understood by the operators.

The criteria of evaluation were enlarged as compared to conventional studies. For example beyond overload of lines & transformers and under voltages in the system, under speed or over speed of generators (permitting to check loss of stability of generating plants), stalling of motors etc. were systematically evaluated during the process.

As an example, one can mention the following case. An optimized "N" (all network elements are in service) situation was considered; one of the incidents is the loss of a line. It led to a low voltage in one substation, to an over speed of two generating units and to the stalling of motor load in six substations. This incident was automatically tackled by SYSCAN within the batch treatment. The reporting at the end of the process suggested checking this particular situation. It showed that the sudden disconnection of the loaded line led to a loss of steady state stability. Increasing inter area oscillations are taking place and finally lead to the loss of synchronism of two generating units.

VII. CONCLUSIONS

This paper summarizes first how the security of supply was guaranteed earlier by means of preventive security margins in operation. It indicates why such approach is presently questionable, and in consequence why traditional approaches cannot be anymore used.

A new methodology based on the concept of "extended electromechanical modeling" is presented allowing for a comprehensive approach of system security. This includes the security study itself, the modeling of emergency control countermeasures, but also the set up of emergency controls themselves, in particular the sizing of devices.

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IX. BIOGRAPHIES

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