A DSA-integrated shedding system for corrective emergency control

G. Giannuzzi[1], R. Salvati, M. Sforna, A. Danelli[2], M. Pozzi, and M. Salvetti

Abstract — The paper describes the design and prototyping of a last generation defense system called Evolved System for Automatic Shedding (ESAS), whose project is currently on-going at the Italian ISO (GRTN). ESAS aims to integrate both Static and Dynamic Security Assessment tools (SSA and DSA) with a state-of-art Special Protection System architecture (SPS), acting on interruptible loads/units with the goal to increase the overall Italian transmission network security.

***Index Terms* — Defense plans, static and dynamic security, load shedding, preventive and corrective remedial actions.**

I. Introduction

The growing security and stability needs, recently pushed in the Italian power network by the on-going privatization and liberalization processes, strongly demand for a more powerful and affordable emergency control system, capable to effectively accommodate and optimize, on-line, both preventive and corrective remedial actions. At the same time, the availability of advanced methods for emergency control, as well as of the recent telecommunication facilities and progressive equipments, permits to develop and implement sophisticated protection schemes, mainly called Special Protection Systems (SPS), which may represent a solution to improve the transmission network security level in a deregulated scenario.

The theoretical approaches, which have largely investigated in the past for the Static and more recently for Dynamic Security Assessment (SSA and DSA), represent an interesting and useful starting point for a revision process of the Italian defense plan. The Italian ISO, Gestore della Rete di Trasmissione Nazionale (GRTN), has initiated some years ago such a process, mainly promoting the refurbishment of the existing system for automatic shedding toward an 'Evolved System for Automatic Shedding' (ESAS). ESAS, based on the integration of SSA and DSA tools with a sophisticated loads/units interruption system, aims to automatically selects the most suitable remedial actions, in a predefined set of allowed maneuvers, for mitigating contingencies scenarios.

The corrective remedial actions are autonomously activated on field and selected on the basis of preventive static and dynamic security analyses. ESAS, conceived for the real-time static and dynamic security assessment and control, represents an evolution of an existing system, actually in operation at GRTN, monitoring overload and tripping events of a set of tie lines, called "critical network sections" (cross-border or internal).

Such evolution has addressed very substantial improvements, as mainly concerns the system architecture, the protection goals, the adaptation rules, the loads/units selectivity and the control room operators' diagnostics.

II. The Italian Defense Plan

The Italian power system had in 2001 a total installed capacity of about 79 GW (21 GW hydro plants, 57 GW thermal plants, 1 GW renewable plants), for an overall energy consumption of 327 TWh (here included auxiliary systems and pumping units), 279 TWh coming for the internal power production and 48 TWh from the neighboring countries exchanges. The Italian transmission system has an overall extension of 65.000 km, here included both AC and DC lines; 16 interconnection border lines and 267 power stations.

For such a large electrical system, an effective defense plan had to be conceived, including all the automatic and manual control actions capable to maintain/restore the power system itself, otherwise passing through an 'alarm status' or evolved to an 'emergency status'. The Italian Defense Plan [1] includes two main levels of remedial actions, those related to the interconnected system operation and those conceived for the islanded grid condition. The first level remedial actions are:

- control of the "critical sections" through a system for automatic shedding (SAS) with fixed thresholds;
- programmed fast tripping of critical generating units through Automatic Tele Tripping Equipment (ATTE);
- manual operation of Emergency Maneuvering Console (EMC), for medium voltage and residential loads, and Interruptible Maneuvering Console (IMC), for high voltage industrial loads;
- programmed action of the Emergency Plan for System Security (EPSS) for rolling blackouts.

The following remedial actions belong to the second class:

- autonomous load shedding action based on frequency relays with fixed thresholds;
- programmed fast tripping of some relevant generating units by Automatic Tele Tripping Equipment (ATTE).

III. The Existing System for Automatic Shedding

For the Defense Plan a set of 420 kV electrical lines is defined as "critical section" if their cascade tripping could evolve to network separation. In the Italian transmission grid the emergency control of critical sections is achieved by a system which aims to prevent separations, interrupting a certain amount of loads in a very short time (less than 1s).

The system trigger is a line tripping event detected in predefined conditions, essentially related to fixed thresholds of power flows through the lines in critical section. Therefore, the operation of this system requires the acknowledgment of both a structural and an operational critical state of the controlled section. In particular, the section is considered

[1] G.Giannuzzi R.Salvati and M.Sforna are with GRTN – Via G. Palmiano, 101 – 00138 Rome, ITALY (e-mail: sforna.marino@grtn.it).

[2] A.Danelli M.Pozzi and M.Salvetti are with CESI – Via R. Rubattino, 54 – 20134 Milan, ITALY (e-mail: pozzi.massimo@cesi.it).

"operationally critical" if at least one of the following conditions is satisfied:

- over-exceeding the so-called "low" power threshold in any lines belonging to section with (k+2) where k lines are out of service;
- over-exceeding the so-called "high" power threshold in any lines belonging to section with (k+3) where k lines are out of service;

Being in principle very different the post-contingency scenarios to be faced, the amount and localization of load to be shedded depends on which lines were out of service in pre-fault conditions, as well as on which threshold has been over-exceeded and which line has tripped. Until now, the structural design of the critical section configuration and power thresholds, as well as the remedial actions, have been off-line defined, based on steady-state and transient studies with different grid configurations and load-flow conditions. In general, the goals of the pursued remedial actions were:

- possible overloads on 420 kV and 245 kV lines have to be limited accordingly to their thermal security limits;
- under-voltage violations have to be everywhere contained and not associated to voltage instability phenomena;
- starting and action of line distance protections, following the electromechanical transients due to remedial interventions, have to be carefully prevented.

Considering the Italian transmission network, the main cross-border and internal critical sections are:

- the overall cross-border section between Italy, France, Switzerland and Austria (Slovenia excluded);
- the partial cross-border section between Italy and France;
- the internal section between the Northern Italy and the Central Italy grids;
- the internal section between the Southern Italy and the Sicily island grids.

IV. The Evolved System for Automatic Shedding

For the last 13 years the existing automatic shedding system have been proving itself to be very effective in increasing the system operation security, mainly in case of contingencies involving lines within critical sections. More precisely, for its design characteristics and conservative tunings, this system has never exhibited lacks of intervention; on the contrary, at least in one case, an inadequate intervention was experienced. However, the complete electric service after the unnecessary shedding was restored in 10 minutes. Due to the increase of power flows and the creation of new critical sections, GRTN [2, 3] has recently initiated the renovation of the existing system toward an evolved one (ESAS), with the goal to solve also some drawbacks and limitations:

- ESAS will be designed and erected through a flexible and modifiable architecture, based on state of art of standard telecontrol and network protocols;
- ESAS will control critical sections continuously following their configurations (i.e. for the insertion of phase-shifter transformers). Then, an adaptation of power thresholds and load shedding strategies will be implemented;
- ESAS will control sections which are not always structurally critical but could become critical only in particular market scenarios or weather conditions;
- ESAS will adapt the load shedding amount to the actual operating conditions related to the critical section, without the risk to activate, for facing the current contingency scenario, an insufficient or excessive interruption;
- ESAS will completely control the cross-border section, including the Slovenia border, and will monitor both the national and the foreign sides of the other border lines;
- ESAS will take into account of the actual load conditions as well as of the possibility to shed pumping units;
- ESAS will be rich of diagnostic information for the control room operator (commands, alarms, warnings).

The goal of ESAS is to apply flexible intervention criteria and shedding strategies on the information coming, in real-time, from SCADA and EMS. At the same time ESAS should integrate SSA and DSA tools with a sophisticated loads/units interruption architecture, distributed on the field and based on standard tele-control equipment and protocols. These key features, which represent the basis for ESAS architecture (Figure 1), can be logically subdivided in two modules:

- the analysis module (ESAS-Analysis) is devoted to study, in both static and dynamic viewpoints, the grid reactions that follow a set of plausible single and multiple contingencies, which are by operator choice or automatically screened and ranked from a specific routine. The analysis module provides, at a preventive stage and starting from the current network state estimated from EMS, the list of possible steady-state and transient network violations, associated to each critical contingency in the examined set, and their index risk;
- the control module (ESAS-Control) is devoted to define, solving a linear programming constrained problem, the optimal load shedding remedial action, on the basis of the actual load forecast or measurements coming from SCADA. For each critical event, this module provides the list of necessary interruptions to be executed, at a corrective stage.

In other words, ESAS-Analysis determines the IF part of the logical rules, distributed on the shedding architecture for their autonomous activation. The THEN part of such rules is defined by ESAS-Control. It aims to achieve a certain corrective security level N-k.

A. The functions of the ESAS-Analysis module

The ESAS-Analysis module computes the steady-state and transient responses of the power system, modeled in detail by sophisticated simulation tools [4, 5] and initialized from the current network state estimation. The list of contingencies may be manually set by operators, or defined according to a statistic extraction, or achieved from the historical archive of the really occurred contingencies. In alternative the contingencies of the list may be automatically screened and ranked based on a N-1 static security or sensitivity analysis.

The complete system, which describe about 450 units, 1000 transformers and lines, 800 loads and some equivalent networks, have to be analyzed. The TD simulations and data analysis lasts from few seconds up to a couple of minutes in the worst cases where voltage or transient instability arise. A parallel computation on a different HW platform perform static N-1 analysis on the same system. This lasts for about a couple of minutes for the whole system, longer when stressed system occours.

The static and dynamic post contingencies responses of the power system are examined in terms of both steady-state violations and dynamic transients, such as voltage instability or collapse, transient instability, cascade line tripping. It is important that the entity of each violation encountered at this stage can be measured in terms of suitable risk indices.

1) Maximum current violations

Line overcurrent or current violations ΔI_L, with respect to the maximum admissible values, are monitored during all the transients, mainly in steady-state conditions, for all the lines with a relevant power flow. Three different intervention thresholds are identified: the most critical one corresponds to an overload for which a timely fast automatic remedial action is necessary, the intermediate and less critical one indicates an overload for which a manual corrective action is sufficient but necessary, the lowest one is related to an overload for which a manual preventive action is suggested for recovering the warning condition.

2) Minimum voltage violations

The voltage violation ΔV_S, with respect to the minimum admissible values, are monitored during all the transients, mainly in steady-state conditions, for all the bus-bars with a relevant power consumption. The verification consists in a comparison between the present value V and the rated voltage V_{MIN}. Different intervention thresholds differentiate automatic corrective and manual corrective/preventive actions.

3) Cascade lines tripping

The cascade line tripping event has been assumed related to the cascade intervention of distance protections. It simply checks the approach of the present value Z of the line impedance to the threshold $Z_{MIN}=1.25Z_{III}$, where Z_{III} is the setting of the third zone level of the related distance protection.

4) Voltage instability and collapse

The electrical variables observed for identifying a voltage instability or collapse scenario are the derivatives $\Delta P_L/\Delta t$ of the power flows through each line and the derivatives $\Delta V_S/\Delta t$ of the bus-bar voltages at their extremes. For each line, if the absolute value of the derived ratio $\Delta P_L/\Delta V_S$ is lower than minimum threshold, a possible voltage instability problem is supposed. A index risk ΔV_R is calculated as the voltage difference between the pre-contingency voltage value V_O and the minimum voltage value V_{MIN} assumed by the trajectory before the irreversible instability and collapse phenomena.

B. The functions of the ESAS-Control module

The ESAS-Control module computes the real and reactive power amounts $\Sigma_C\Delta P_C$ and $\Sigma_C\Delta Q_C$, to be shed for facing the examined dangerous contingencies. These amounts are associated to a combination of load interruptions or generator trippings, derived from an on-line solving of an optimization problem. At the same time, it tries to mitigate different violations and to reduce the shedding strategy costs. Once solved this problem, the ESAS-Control module verifies also the effectiveness of the suggested remedial actions, whenever such a verification is not implicit in the optimization method. More precisely, the critical scenarios associated to static events may be directly solved and verified by non-linear approaches, such as resolution methods with integrated load-flow. On the contrary, critical scenarios associated to dynamic events may be firstly solved by linear approaches, such as sensitivity based methods, and then post-verified with the complete dynamic analysis and simulation of corrective actions. To formulate the control problem as a linear programming one, the sensitivity matrices between the singular real and reactive sheds, ΔP_C and ΔQ_C, and the risk indices (steady-state overloads ΔI_L, steady-state voltage violations ΔV_S, cascade line tripping due to protections ΔZ_P, voltage instability and collapse risk ΔV_R) are necessary.

1) Sensitivity matrices computation

The necessary sensitivity matrices necessary to formulate the linear programming control problem are presently calculated off-line (partially on-line in the future) by using static computation tools, which solve the complete 420-245 kV transmission and 165-145 kV sub-transmission networks, initialized from a significant, or better, the last state estimation. The monitored lines and bus-bars, as well as the loads and units under automatic shedding, are modeled in detail. More precisely the following sensitivity matrices are computed:

- intermediate sensitivity of the active ΔP_T and reactive ΔQ_T powers, through the transformers between transmission and sub-transmission networks, with respect to active ΔP_C and reactive ΔQ_C amounts, separately shed ($\Delta P_T/\Delta P_C$, $\Delta P_T/\Delta Q_C$, $\Delta Q_T/\Delta P_C$ and $\Delta Q_T/\Delta Q_C$). This computation requires the complete description of the two networks and it is practicable off-line;
- intermediate sensitivity of each particular index risk, basically all achievable from the line currents ΔI_L and the bus-bar voltages ΔV_S variations, normalized with respect to the active ΔP_T and reactive ΔQ_T amounts, separately varied ($\Delta I_L/\Delta P_T$, $\Delta I_L/\Delta Q_T$, $\Delta V_S/\Delta P_T$ and $\Delta V_S/\Delta Q_T$). This computation requires only the model of transmission network and is, in principle, practicable also on-line;
- final sensitivity of each particular index risk, basically all achievable from the line currents ΔI_L and the bus-bar voltages ΔV_S variations, normalized with respect to the active ΔP_C and reactive ΔQ_C amounts, separately shed ($\Delta I_L/\Delta P_C$, $\Delta I_L/\Delta Q_C$, $\Delta V_S/\Delta P_C$ and $\Delta V_S/\Delta Q_C$). This computation requires the complete model of both transmission and sub-transmission networks and it is practicable only off-line, unless to use approximations based on the previous intermediate sensitivities, which allow a partially off-line and partially on-line computation.

2) Analysis of intermediate sensitivity matrices

An analysis of the intermediate sensitivity matrices used for formulating the linear programming problem within the ESAS-Control module ($\Delta P_T/\Delta P_C$, $\Delta P_T/\Delta Q_C$, $\Delta Q_T/\Delta P_C$ and $\Delta Q_T/\Delta Q_C$) puts in evidence the following considerations:

- there is a clear de-coupling between the intermediate sensitivities of the active and reactive powers flowing through transformers with respect to the loads or units under shedding. The direct terms $\Delta P_T/\Delta P_C$ and $\Delta Q_T/\Delta Q_C$ prevail with respect to the indirect terms $\Delta P_T/\Delta Q_C$ (generally negligible) and $\Delta Q_T/\Delta P_C$ (which could be easily interpolated for achieving higher results accuracy);
- the significant transformations, whose power flow is really affected by the power shedding, represent only a portion of the total virtual border between transmission and sub-transmission networks. The sums of direct ($\Sigma_T\Delta P_T/\Delta P_C$ and $\Sigma_T\Delta Q_T/\Delta Q_C$) and indirect ($\Sigma_T\Delta P_T/\Delta Q_C$ and $\Sigma_T\Delta Q_T/\Delta P_C$) terms shows that about 80 of the 320 auto-transformers of the Italian grid are not affected by the loads/units shedding;
- the significant transformations, whose power flow is strongly affected by the power shedding, prove the actual splitting up of the sub-transmission networks in load islands, where only few transformers have relevant direct terms $\Delta P_T/\Delta P_C$ and $\Delta Q_T/\Delta Q_C$. The intermediate sensitivity matrix is therefore basically diagonal and reflects the longitudinal structure of the Italian transmission grid.

3) Analysis of final sensitivity matrices

A numerical analysis of the final sensitivity matrices used for formulating the linear programming problem within the ESAS-Control module (ΔIL/ΔPC, ΔIL/ΔQC, ΔVS/ΔPC and ΔVS/ΔQC) puts in evidence the following considerations:

- there is a clear de-coupling between the final sensitivities values of the line currents and bus-bar voltages with respect to the loads or units under shedding. The direct terms $\Delta I_L/\Delta P_C$ and $\Delta V_S/\Delta Q_C$ prevail with respect to the indirect terms $\Delta I_L/\Delta Q_C$ and $\Delta V_S/\Delta P_C$;
- the loads or units available for shedding are generally sufficient to control the main line current overloads and bus-bar voltage violations. Only about 70 of the 570 lines and about 100 of the 770 substations are affected very small by the available load shedding;
- the propagation of the control actions along the longitudinal structure of the transmission grid is higher for direct ($\Delta I_L/\Delta P_C$ and $\Delta V_S/\Delta Q_C$) than for indirect terms ($\Delta I_L/\Delta Q_C$ and $\Delta V_S/\Delta P_C$);
- the propagation of control actions is better for the active terms (ΔIL/ΔPC and ΔVS/ΔPC), while the reactive terms (ΔIL/ΔQC and ΔVS/ΔQC) have a local and limited effect.

4) Shedding strategy optimization

Once determined the final sensitivity matrices between each particular index risk and the active ΔP_C and reactive ΔQ_C amounts the following linear programming problem is set out:

$$\min OF = \sum_{j=1}^{NA} C_{Aj} X_{Aj} \ , \qquad 0 \le X_{Aj} \le 1$$

where:

- OF represents the objective function to be minimized, related to the total cost of the shedding strategy;
- X_{Aj} represents the structural variables (on the columns of the linear system) related to the shedding percentage of each j-aggregation (loads or units interruptible simultaneously and with the same command). In principle, the problem should be set out with only quantized solution admissible (status of breakers);
- C_{Aj} represents the costs of j-aggregate, deriving from the specific costs c_{Pk} and c_{Qk} of the active P_{Ck} and reactive Q_{Ck} sheds. This computation required the actual measurements (or estimation) of MW and MVAr of loads or units:

$$C_{Aj} = \sum_{k=1}^{NC_j} \left(c_{Pk} P_{Ck} + c_{Qk} Q_{Ck} \right)$$

The auxiliary variables (on the rows of the linear system) represent the line current reductions ΔI_{Li} or the bus-bar voltage increases ΔV_{Si}, to be achieved from the shedding strategy in respect of the objective function *OF*, playing a role of constraints in the linear programming problem:

$$\Delta I_{Li} \ge \sum_{j=1}^{NA} S_{LiAj} X_{Aj} \ , \ S_{LiAj} = \sum_{k=1}^{NC_j} \left(\frac{\Delta I_{Li}}{\Delta P_{Ck}} P_{Ck} + \frac{\Delta I_{Li}}{\Delta Q_{Ck}} Q_{Ck} \right)$$

$$\Delta V_{Si} \ge \sum_{j=1}^{NA} R_{SiAj} X_{Aj} \ , \ R_{SiAj} = \sum_{k=1}^{NC_j} \left(\frac{\Delta V_{Si}}{\Delta P_{Ck}} P_{Ck} + \frac{\Delta V_{Si}}{\Delta Q_{Ck}} Q_{Ck} \right)$$

where:

- S_{LiAj}, R_{SiAj} and Q_{PiAj} respectively represent the sensitivity of the i-line current, the i-station voltage and the i-protection impedance with respect to the j-aggregate;
- $\Delta I_{Li}/\Delta P_{Ck}$ and $\Delta I_{Li}/\Delta Q_{Ck}$ represent the sensitivities of the i-line current with respect to the k-load;
- $\Delta V_{Si}/\Delta P_{Ck}$ and $\Delta V_{Si}/\Delta Q_{Ck}$ represent the sensitivities of the i-station voltage with respect to the k-load;
- P_{Ck} and Q_{Ck} represent the k-load instantaneous values (or its estimated value) of their real and reactive powers. These values have to be carefully filtered, properly selecting the load aggregations, for avoiding too rapid changes in the optimal shedding control problem and solutions.

The solution of the linear programming problem computes the optimal combination of loads and units to be shed, in such a way to solve at the minimum cost all the network violations. In such a formulation it is easy to introduce preferential actions such as: tele-tripping of a generator, opening of an overloaded 245 kV line without significant consequences on the nearby 420 kV lines, as well as adoption of conservative margins.

5) Shedding effectiveness verification

The verification of shedding strategy is performed by means of the same procedures previously used by the ESAS-Analysis, in presence of contingency scenarios inclusive of corrective control remedial actions. The possible causes of imprecision, requiring the introduction of conservative coefficients, are:

- linearization error, affecting both the computation of the sensitivity matrices and the related superposition effects. This error may be attenuated using realistic shedding amounts during the sensitivity computation phase, as well as introducing suitable corrective factors depending from the instantaneous values of the active and reactive shed;

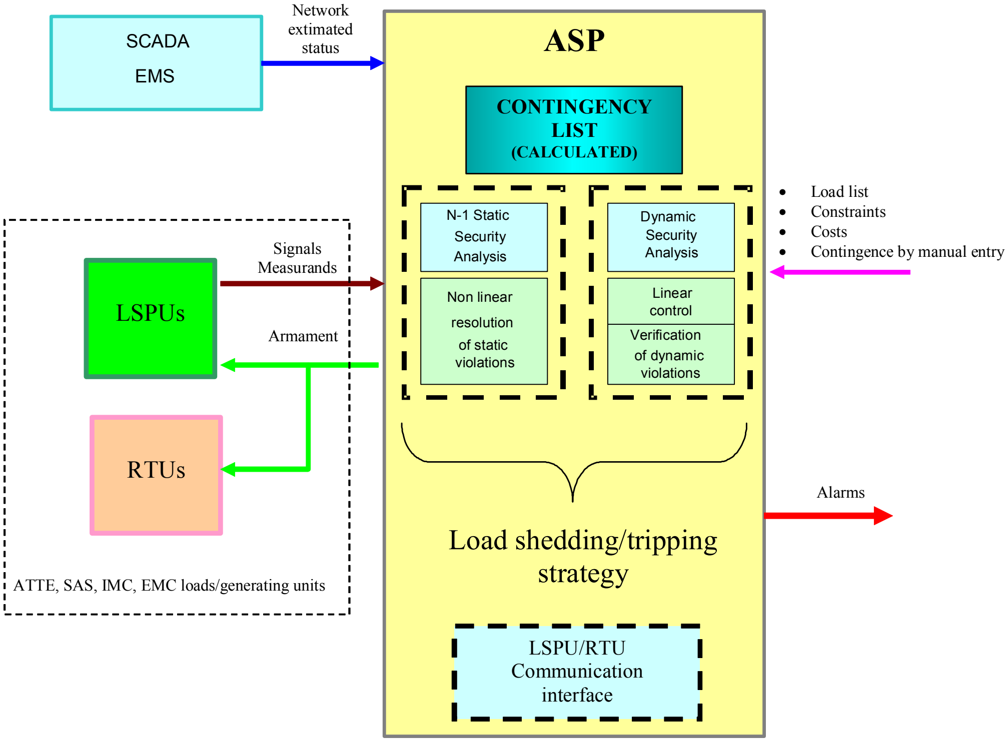

Fig. 1 – Overall architecture of the Automatic Shedding Processor (ASP): on the left side it is shown the interconnection of existing ATTE, SAS, EMC and IMC (exchanging with Load Shedding Peripheral Units - LSPU - and Remote Terminal Units RTU: tele-measurements TM, tele-signals TS, alarms and rules), on the right side it is shown the architecture of SSA and DSA modules, providing ESAS-Analysis and ESAS-Control functions, acquiring information from SCADA and EMS (state estimation), and exchanging data with ATTE, SAS, EMC and IMC (load configuration and measurements, control rules and sensitivity data).

- modeling error, related to the description of actual loads behavior. This error may be reduced using more precise static and dynamic models, mainly for large voltage or frequency variations in the post-contingency scenario;
- biasing error, suggesting too much extended shedding maneuvers, mainly in case of significant network violations with reduced shedding resources. This error may be attenuated pre-filtering too low sensitivity values, related to components very far from the violations.

6) Shedding arming on the field

After these analyses, which can take some minutes, it is foreseen that the central system remotely prepares (arms) the peripheral devices, in the grid sections potentially exposed to static or dynamic risks, with the corrective control actions needed to face the related critical contingency. The armament is calculated and implemented upon each significant variation occurring of the power system's operating condition.

To configure the proper action at the devices on field some second are needed. Once armed the shedding action on the field, if an event occurs, noticeable through a protection tripping, the event detector sends the information to all the possible recipients, using a multicast transmission method, the latest to avoid the saturation of the telecommunication channels. Upon reception of the information that a specific event occurred, only the devices previously armed for that event will execute the shedding action (Figure 2). In spite of the fact that an amount of time is needed to configure the system, if a critical event occurs, it can be tackled by few hundreds of milliseconds in average.

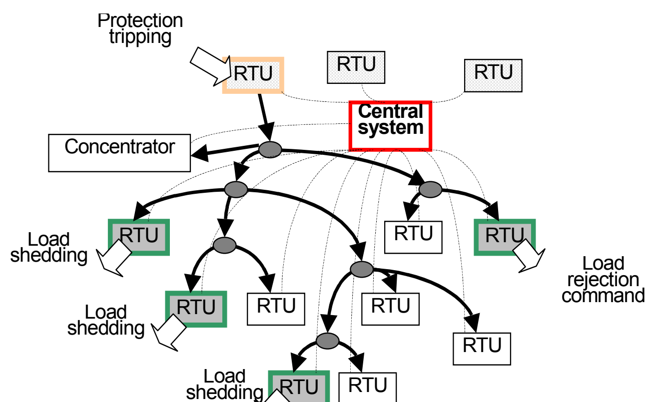

Fig. 2: Flow of actions following the detection of an occurred critical event.

V. The ESAS Experimentation on the Italian Grid

A prototype of the ESAS-Analysis and ESAS-Control modules has been running under experimentation at GRTN National Control Center since the end of 2002.

A. The interruptible loads configuration under test

the list of interruptible loads associated to EMC and IMC are continuously upgraded by GRTN . Some residential and industrial loads, due to their particular position and demanded power, belong to the first group (EMC) and they can be shed by GRTN operators only in emergency conditions, even without specific contracts. Other relevant consumers, which have subscribed power interruptible contracts (with or without pre-notice), belong to the second group (IMC) and can be disconnected by either preventive control or corrective remedial action.

An analysis of the instantaneous power consumption of the interruptible loads (IMC) shows that:

- the sum of each interruptible load aggregate does result always lower than its contractually expected value. This is because the power aggregate depends strongly on the variable consumption level of the interruptible loads, which are mainly, nowadays, arc-furnaces. The actual nature of interruptible loads is therefore almost stochastic than deterministic, and it strongly depends on statistic superposition of different working cycles which typically characterize the steelworks industry;
- it appears important to properly select the interruptible loads aggregates, with the aim to reduce as much as possible the short-term power swings.

Most of the substations in the Italian system and the IMC load are equipped with devices performing fast communication that satisfy the emergency control requirements. Specifically, substations are equipped with configurable Remote Terminal Units (RTU) that can be set from the control center.

B. *The ESAS-Analysis module results*

To describe the results provided by ESAS-Analysis, it was considered the N-1 and N-2 security analyses, carried out on the cross-border section of the Italian transmission grid, for the network situations referred to the state estimations from Sep/24/2002 to Nov/27/2002. Such situations often present, also without contingencies (N security), some overloaded 245 kV lines ($I>I_{MAX}$), for which no remedial control action is automatically taken. In the analyzed situations the transmission network resulted, as expected, quite robust in front of both cross-border and internal contingencies. Some criticisms have been put in evidence, mainly on the cross-border section and on some relevant Northern lines, starting from the N-2 security level. These results, even if they cannot be generalized all over, are representative of the present Italian transmission grid scenario. All the encountered realistic violations (Table 1) are line current overloads, but voltage violations arise only on over-stressed transmission network, which is unrealistically.

C. *The ESAS-Control module results*

To illustrate the results provided by ESAS-Control, it was considered the N-1 and N-2 remedial actions, designed to control the cross-border section of the Italian transmission grid, for the network situation referred to the state estimation of a working day of September 2002 at 11.00 a.m.

Different shedding strategies have been compared, recovering the current overloads with continuous or quantized sheds, changing the linear problem input data and considering equal, or different, costs between EMC and IMC shedding actions:

a) without corrections to recover linearization errors;
b) with corrections to recover linearization errors;
c) without corrections and without load aggregations;
d) without corrections and with quantized shedding;
e) with corrections at different thresholds;
f) with different costs between EMC and IMC shedding and without corrections to recover linearization errors;
g) without conservative corrections at different grid conditions from those used during sensitivity computation.

Assuming case a) results as a reference of the shedding actions, Table 2 represents, for each shedding strategy:

- the total amount of normalized active $\Delta P_C/\Delta P_C'$ and reactive $\Delta Q_C/\Delta Q_C'$ powers shed. Values lower or higher than 1 p.u. respectively mean a shedding efficiency greater or lower than those achieved in case a).
- the recovery ratio representing an effectiveness index of the remedial action. Values lower or higher than 1 p.u. respectively mean a shedding insufficient or excessive;
- the shedding control strategy, in terms of number of aggregations to be partially (0 - 100 %) or completely (100 %) interrupted through EMC or IMC.

ESAS-Analysis: POST-CONTINGENCIES VIOLATIONS		
No contingency (N security)	Light current violations	Heavy current violations
Intact cross-border (420 and 245 kV)	1 line (245 kV)	
Single contingency (N-1 security) [Line name (rated voltage)]	Light current overload violations	Heavy current overload violations
Venaus-Villarodin (420 kV)	3 lines (245 kV)	1 line (245 kV)
Rondissone-Albertville-I (420 kV)	2 lines (420 kV) 4 lines (245 kV)	1 line (245 kV)
Rondissone-Albertville-I-II (420 kV)	2 lines (420 kV) 5 lines (245 kV)	1 line (420 kV) 1 line (245 kV)
Musignano-Lavorgo (420 kV)	2 lines (420 kV) 2 lines (245 kV)	1 line (245 kV)
Bulciago-Soazza (420 kV)	2 lines (420 kV) 1 line (245 kV)	1 line (245 kV)
Redipuglia-Divaccia (420 kV)		2 lines (245 kV)
Avise-Riddes (245 kV)	1 line (245 kV)	1 line (245 kV)
Valpelline-Riddes (245 kV)	1 line (245 kV)	1 line (245 kV)
Pallanzeno-Morel (245 kV)	2 lines (245 kV)	
Ponte.-Airolo (245 kV)	2 lines (245 kV)	
Sondrio-Robbia (245 kV)	1 line (245 kV)	
Camporosso-Broccaros (245 kV)	1 line (420 kV) 1 line (245 kV)	
Soverzene-Lienz (245 kV)	1 line (245 kV)	
Padriciano-Divaccia (245 kV)	1 line (245 kV)	
Double contingency (N-2 security)	Light current violations	Heavy current violations
Redipuglia-Divaccia (420 kV) Padriciano-Divaccia (245 kV)	1 line (420 kV) 1 line (245 kV)	1 line (245 kV)
Triple contingency (N-3 security)	Light current violations	Heavy current violations
Redipuglia-Divaccia (420 kV) Padriciano-Divaccia (245 kV) Soverzene-Lienz (245 kV)	3 lines (420 kV) 3 lines (245 kV)	

Tab.1 – Experimentation results of the ESAS-Analysis prototype: for each single (N-1), double (N-2) or triple (N-3) contingency the amount of current overloaded lines (operated at both 420 kV and 245 kV) is reported, distinguishing between light and heavy current violations.

The comparison with different costs, test cases a) and f), put in evidence that the linear programming problem solver aims to shed before load aggregations under IMC (with lower costs, 0.1 p.u.) than those under EMC (with higher costs, 1.0 p.u.).

The conservative corrections, test cases b) and e), aims to recover linearization errors due to post-contingency variations. With separate loads and no cluster aggregations, test case c), the optimized load shedding amount results to be reduced, due to the increased number of structural variables. On the contrary, if the linear programming problem is set out with only quantized solutions, test case d), due to the admissible solutions constraints, the optimized load shedding is increased. The introduced intervention and recovery thresholds, test cases e), aim to differentiate the shedding criteria according to the Italian transmission grid characteristics and operators' experience. For overloads up to a first intervention threshold, where also manual re-dispatching can be accomplished, no remedial actions are taken. For overloads up to a second intervention threshold, manual shedding actions can be assessed at a preventive control level for reaching a recovery threshold. For overloads up to a third intervention threshold, manual shedding represents a necessary and sufficient corrective control and actions are suggested by linear programming problem solver as well. For heavy overloads, above a third intervention threshold, automatic shedding is requested and possibly optimized. With grid conditions different from those used for sensitivity computation, test cases g), the shedding optimization remains adequate, both in off-peak and peak load conditions, also changing the thermal current limits of lines.

VI. Conclusions

The paper described the architecture and the main functions of an emergency corrective control system called 'Evolved System for Automatic Shedding', whose design is currently on-going at the Italian ISO (GRTN). A short description of the ESAS-Prototype, since 2002 under experimentation at the National Control Center, has been also given introducing:

- the Analysis module functions, for the computation of index risks related to maximum current violations, minimum voltage violations, cascade line tripping and voltage instability and collapse;
- the Control module functions, for the sensitivity matrices computation and analysis, shedding strategy optimization and effectiveness verification.

Some results of the ESAS-Prototype, currently applied on the Italian grid, have been lastly presented. They concern the performances of the ESAS-Analysis module and a variety of shedding strategies proposed by the ESAS-Control module. Some results of the analysis carried out on the current and voltage sensitivity matrices, have been also reported. The formulation of the control problem as a linear programming one, beside to be a simple and feasible approach, supported by effective numerical methods and tools, has proved itself to be quite flexible to introduce shedding costs, and remedial actions based on units and loads tripping. Such a formulation allowed also to correct sensitivity matrices and constraints, for conservative control margins.

At present, ESAS project appears quite well conceived and the related prototype is giving very promising results. The ESAS-Prototype will be a benchmark at GRTN for the static and dynamic security assessment methods, as well as for the preventive and corrective emergency control approaches, whose interest will certainly increase in the new deregulated energy market scenarios.

Future developments will foresee the integration of the voltage and phases measurements coming from a set of Phase Measurements Units (PMU) already planned inside the GRTN Wide Area Measurement System (WAMS). As an example, the detection of dynamic instability could firstly focus the dynamic analysis on specific areas of the power control.

ESAS-Control: CORRECTIVE REMEDIAL ACTIONS					
Double contingency (N-2 security)	Rondissone-Albertville-I-II (420 kV) Musignano-Lavorgo (420 kV)				
Network situation Working day at 11:00 a.m.	$\Delta P_c / \Delta P_c'$	$\Delta Q_c / \Delta Q_c'$	Rec. ratio	Aggreg. EMC	Aggreg. IMC
a) equal costs no corrections	1.00	1.00	1.76	16 (100%) 1 (89%)	3 (100%)
b) equal costs linear corrections	0.66	0.53	1.20	10 (100%) 1 (40%)	1 (100%)
c) equal costs no corrections no aggregations	0.97	0.97	1.50	243 (100%) 1 (93%)	
d) equal costs no corrections integer shedding	1.01	0.99	1.76	19 (100%)	3 (100%)
e) equal costs linear corrections int. thres. = rec. thres.	0.15	0.16	1.03	1 (100%) 1 (89%) 1 (69%)	0
e) equal costs linear corrections int. thres. > rec. thres.	0.13	0.14	0.97	2 (100%) 1 (64%)	1 (100%)
f) different costs no corrections	1.02	0.97	1.77	13 (100%) 1 (24%)	9 (100%)
Different Network situation 22 January 2003 h 03:00	$\Delta P_c / \Delta P_c'$	$\Delta Q_c / \Delta Q_c'$	Rec. ratio	Aggreg. EMC	Aggreg. IMC
g) equal costs no corrections no-load condition	0.51	0.50	1.60	5 (100%) 1 (44%) 1 (97%)	1 (100%)
Different Network situation 22 January 2003 h 11:00	$\Delta P_c / \Delta P_c'$	$\Delta Q_c / \Delta Q_c'$	Rec. Rati	Aggreg. EMC	Aggreg. IMC
g) equal costs no corrections peak-load condition	0.74	0.73	1.84	9 (100%) 1 (42%)	1 (100%)

Tab.2 – Experimentation result of the ESAS-Control prototype: for each shedding strategy (a-g) the normalized total amount and effectiveness of load shedding (operated under both EMC and IMC) are reported, specifying the number of load aggregation totally and partially shed.

VII. References

[1] GRTN, "Piani di difesa del sistema elettrico", Documento IN.S.T.X.1006, http://www.grtn.it, in Italian.

[2] GRTN, "Sistema di elaborazione distacchi automatici, Specifiche funzionali generali", Documento DRRPX02006, http://www.grtn.it, in Italian.

[3] L.Franchi, A.Gambelunghe, R.Salvati, M.Sforna, "Online Dynamic Security Assessment at the Italian Independent System Operator", Bologna IEEE Powertech, 2003.

[4] M.Agostinelli, G.Demartini, L.Franchi, M.Mocenigo, "CRESO: an efficient use of the on-line data with a suite of programs for the off-line network analysis", CIGRE SC39 Colloquium, June 1989.

[5] P.Baratella, P.Scarpellini, R.Marconato, B.Cova, E.Gaglioti, R.Zacheo, "A power system simulator covering different time scale phenomena: models, algorithms, MMI and test results", IEEE Powertech, 1995.

VIII. BIOGRAPHIES

Giorgio Giannuzzi received his Doctor of Electric Engineering degree from the University of Rome in 1996. Until December 2000 he worked for ABB, where he was in charge of network studies, protection and control applications. In the same period, he was involved with the SCTI project (new Italian national SCADA/EMS control system), with special reference to RTU apparatus and data engineering issues. Since January 2001 he works for GRTN as expert in protection, telecontrol and substation control systems.

Marino Sforna received his Doctor of Electric Engineering degree from the University of Rome in 1985. He joined ENEL in 1982 as a network designer. From 1987 to 1997, he was with the R&D Department where he gained experience in artificial intelligence applied to power system operations. From 1997 to 2001, he was the deputy manager of the GRTN-Area Control Center of Milan. Presently, among other his other activities, he is responsible for defense plans and restoration strategies at GRTN.

Roberto Salvati received his Doctor of Electric Engineering degree from the University of Rome in 1984. In 1987 he joined to the National Control Center of ENEL where he worked in the field of network static and dynamic simulation. From 1992 to 1997 he worked in ENEL-Area Control Center of Rome as a Senior Technician in the fault analysis and protection setting. Since 1998 he is working in defying protection setting standards, defense plans and restoration strategies at GRTN.

Massimo Pozzi received his Doctor degree in Electronics (Automatic Systems), from the Polytechnic of Milan (Italy) in 1987. In 1989 he joined to the Automatica Research Center of ENEL, where he worked as Researcher in the control system and voltage regulation department. Then he worked at ENEL Ricerca from 1997, as Senior Researcher in the framework of grid voltage control and power electronics application. Since 2000 he is working at CESI as Product Leader, in the framework of grid supervision and control.

Massimo Salvetti received his Doctor degree in Electrical Engineering (Energy Automation) from the Polytechnic of Milan in 2001. In the same year he joined CESI S.p.A. in Milan (Italy), where his area of interest includes power system analyses, simulation and control.

Aldo Danelli received his Doctor degree in Electronics (Mathematics), from the Polytechnic of Milan (Italy) in 1998. In 1989 he joined the Automatica Research Center of ENEL, where he had worked as Researcher in the control system and voltage regulation department. Since 2000 he has been working at CESI in the framework of grid supervision and control.