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GUIDELINES FOR ISO OPERATOR AID AND TRAINING FOR POWER SYSTEM RESTORATION IN OPEN ELECTRICITY MARKETS

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Abstract

Plans to defend and restore electric energy systems have been historically developed all over the world to provide a rapid and secure recovery of a normal operating condition.

Migration from vertically integrated utilities to open access environment poses the question, particularly felt in Europe, to reassess the basis of such plans in order to hold equal, or even better, standard of system security.

In Italy, in particular, the restoration of a power system after a blackout has made use up to now of the black-start capability of selected hydro power stations (named 'early-restoration plants') through pre-established paths called 'restoration lines'. With the unbundling and liberalization of the electrical energy systems, some studies have been recently carried out for assessing the possible contribution to the restoration plan from thermal units. Some results relevant to geothermal plants, to steam power plants repowered with gas turbines and to combined heat and power generating plants are included in the paper.

The paper reports also on additional topics to consider while developing defense and restoration plans in deregulated regional/national systems. Such elements constitute the skeleton of an intelligent supporting, and training, aid for independent system operator (ISO) control center personnel.

1 Introduction

In Italy, and in most European countries, the liberalization of the electric power market is introducing multiple, new participants, split responsibilities and is causing the definition of quite precise rules to govern power and energy service.

Unfortunately, ancillary service provision strategies have instead been derived, with insufficient deal of criticism, from former structures, mainly related to national, vertically integrated network management.

Moreover, while contractual agreements with distribution utilities and final users were considerably tested, reduced experiences have been matured so far, in dealing with required behaviors of generation companies, especially in emergency conditions. In other words, it is still under question if it becomes more efficient, and therefore profitable, to leave the ISO complete co-ordination of protection and control systems when avoiding network separations or recovering from blackouts.

Anyway, it is widely accepted that multiplicity of ownership increases risks of emergency, due to often-conflicting interests among committed parties.

To provide some elements on the amount of work that needs to be done, the paper starts from the examination of the Italian defense and restoration plan, with the aim of providing guidelines for improving its efficiency and for supporting control center operators in decision making, and training, during real, or simulated, emergency conditions.

In Italy the restoration of a power system after a blackout has made use up to now of the black-start capability of selected hydro power stations (named 'early-restoration plants') through pre-established paths called 'restoration lines'. Section 3 summarizes the results of some studies that have been recently carried out for assessing the possible contribution to the restoration plan from thermal units, and, in particular, from geothermoelectric plants, from steam power plants repowered with gas turbines and from combined heat and power generating plants.

The results constitute the basis for an under development expert/simulation tool to be considered for possible application in the ISO national and regional districts. This expert/simulation tool is described in section 4.

2 Italian Defense and Restoration Plans

Recent redistribution of roles within the European electric power system environment caused the institution of national or regional ISOs, who are responsible for transmission grid operation, and act to hold predefined levels of security and quality of service.

Defense plans aim at maintaining a normal working point in a system evolving towards emergency, as well as to recover to a normal condition a still emergency operating grid.

Normal and emergency conditions are defined according to a broadly accepted state diagram (and possible extensions) [1, 2] and commonly considered security criteria (n-1, and so on), where control actions provide recovering transitions.

European countries usually distinguish, according to the different type of experienced emergency, between automatic and manual interventions, and also develop different strategies according to interconnected and isolated conditions.

Defense plans try to anticipate dangerous trends towards blackout conditions, and express themselves to overrule conventional protection interventions. Roughly speaking, they behave like secondary control loops with regard to local protection systems, since they point to an area secure management.

If every protective measure proves unsuccessful, part, of reduced or significant extension, of the transmission grid reaches a blackout condition.

Such an in extremis working point is recognized and assessed according to criteria considering abrupt voltage and frequency decays and power abnormal oscillations, but some of them would be probably avoided by profiting of advanced monitoring devices [3], able to assure a network state estimation also during emergencies, and by driving specific controls.

When blackout is reached, restoration plans become effective, committing

- black-start resources to reenergize radial transmission paths for subsequent ballast load insertion;
- parallel operation of large thermal units;
- generation ramping;
- interconnection between restored paths and
- final complete load recovery.

2.1 Remarks on present form of defense and restoration plans

As earlier mentioned, plans to defend and recover electric transmission system in deep emergency conditions were elaborated with reference to vertically integrated national utilities.

Due to this point, manual and automatic corrective measures were considered to be performed under supervision of regional/national control centers, so that open access environment forces towards specific contractual agreements to propose the same procedures.

Apart from this crucial item, defense and restoration plans seldom show significant degree of reciprocal co-ordination: while the former act with local or diffuse generation tripping and/or load shedding, the latter looks for black-start sources and restoration paths to re-energize.

Partial or complete blackout conditions are preceded by network separation phenomena (driven by cascading outages, protection incorrect tripping and unavailable components under maintenance), which determine isolated subsystems operating at different frequencies.

Load shedding relays, as well as generation tripping ones, in single or progressive interventions should theoretically guide the grid to new equilibria, with reduced energy exchanges, but with the chance to operate a load recovery and a network re-synchronization as well.

Transient behaviors of an electric system under separation may lead to incorrect generation tripping, or creation of surviving subsystems with internal shortage of generation resources.

Under frequency operation in areas with prevailing thermal generation can cause blackout in the following cases:

- The internal generation/load mismatch is so relevant that load-shedding relays prove unsuccessful to restore acceptable frequencies, taking into account of users with preferential contracts or significant social impact.
- Thermal units are not provided with load rejection facilities and no special defenses are implemented to tailor appropriate load areas around them.
- Thermal units are equipped with load rejection facilities, but these are activated by a load drop anticipating relay, rated at the minimum operating real power level (30-40% of the rated power in case of supercritical UP boiler, with low pressure flash tank). In such a particular case, when insufficient hydroelectric and gas turbines groups are present in the considered area, even if a new equilibrium point could be reachable, the required generation profile is unsustainable for large thermal units, so that the subsystem collapses.

The Italian geographical configuration, in addition to its frequent dependence in energy supply from neighboring countries, suggests high probability of black out after separations. If this process results in isolated areas with either reduced local generation, or prevailing part of UP thermal units, defense plans become useless to rescue the under-frequency subsystem.

At the time being, Italian defense plans accounts for load shedding protective system, only used within major urban areas. Moreover, the only link with restoration plan is the constraint of not involving ballast loads for restoration paths in load shedding relays area of influence.

Under these limits, it is stressed that the present restoration plan is elaborated for complete loss of power supply. In other words, restoration paths, including sequences of predefined maneuvers, develop from assigned black start units regardless of how the system came to such in extremis condition. There is only a limited chance for the regional control system operator to stop the restoration path building whenever a surviving area is identified to be significant for large thermal unit restoration.

Unfortunately, this profitable 'change of mind' requires supervision activity by operation centers, and complete availability of communication channels, of doubtful efficiency in black out conditions. Section 4 will provide some guidelines for operator aid and training for power system restoration in open access environment.

An other issue is that, as already mentioned, the Italian restoration plan requires that the black-start maneuver is started from by selected hydro power stations. The turbines of these stations are equipped with a special speed governor and are devoted to start-up thermal units through pre-established paths called 'restoration lines'. Because of the great distance between those early-restoration hydro plants and some important thermoelectric groups station belonging to the southern (and more stretched) part of the Italian HV transmission network, in the past some studies have already been carried out for assessing the possible contribution of conventional thermal units to the restoration plan. The unbundling and liberalization of the electrical energy systems has justified further investigations. The main results of some recent studies are summarized in the following section.

3 Black startup capability of thermoelectric power plants

The deregulating process now being developed in most of industrialized country in the energy sector has received a strong impulse by the new technologies now available for power generation. In fact the CCGT (Combined Cycle Gas Turbine) technology allows the operators (often non-electric utilities) to rapidly build and put in service high efficiency and low investment power plants. In several cases obsolete steam plants have been repowered by adding a first stage based on gas turbines.

Therefore the power plant scenario is rapidly changing and these new resources must be regarded as powerful tools for improving the power system reliability.

Moreover, the developments in the power electronics technology can give a strong impulse to exploit power plants usually not adopted for restoration purposes.

A review of the studies recently carried out to assess these possibilities is reported here, with main reference to:

- geothermal power plants;
- steam power groups repowered with gas turbines;
- autoproducers and combined heat and power generating systems

3.1 Geothermal power plants

In some regions among the world, geothermal fluids are available relatively close to the ground surface. This allows building steam power plants exploiting this natural and cheap source.

Geothermal power plants are characterized by a simple steam cycle, which allows operating units of outstanding reliability and yearly availability higher than 8000 hours. Usually these plants are designed and classified to supply the base load in the grid and are not structured to provide network services.

Normal start-up of such units requires the energisation of the auxiliaries, usually by the primary distribution network. In the case of emergency conditions, the power plant performs a load rejection maneuver and remains in operation islanded on its own auxiliaries. However this maneuver sometimes fails, due to auxiliaries' protection intervention caused by inadequate design.

The possibility of improving the unit performance during emergencies and during restoration procedures by means of the installation of a SWVC [4] (Static Watt Var Compensator) has been tested. The installed device should allow feeding the auxiliaries on a separate and stable source during major system disturbances and start the geothermal power plant in blackout conditions.

SWVC power and battery storage energy ratings are basically designed to provide the power needed to start the condenser extraction pump during the black-start maneuver, and to feed the electrical auxiliaries until the main generator can feed them on a separate island.

In Italy, there are circa 30 geothermal power plants, with an installed capacity of more than 800 MW. One of them (the Valle Secolo power plant) consists of 2 units of 60 MW each. A study [5] has been recently carried out to assess its capability to energize, after a blackout, the electrical auxiliaries of one of the four 320 MW groups of the steam power station located near Piombino.

Referring to the scheme of Fig. 1, showing the geothermal and the steam plant, the following steps in the restoration procedure can be identified:

- keep the auxiliaries fed on a separate network in case of a major disturbance to lead to a "soft load rejection", or, in case of failure;
- start the auxiliary services of the geothermal plant by means of the SWVC, and start the geothermal plant turbine, excite the generator, and transfer the auxiliaries' supply to the generator;
- energize the 132 kV connection to the auxiliaries of the steam plant;
- start the auxiliaries and the steam turbine;
- synchronize the steam power plant, after the energisation of 132/400 kV transformer ATR, and ramp the steam plant to its minimum power limit.

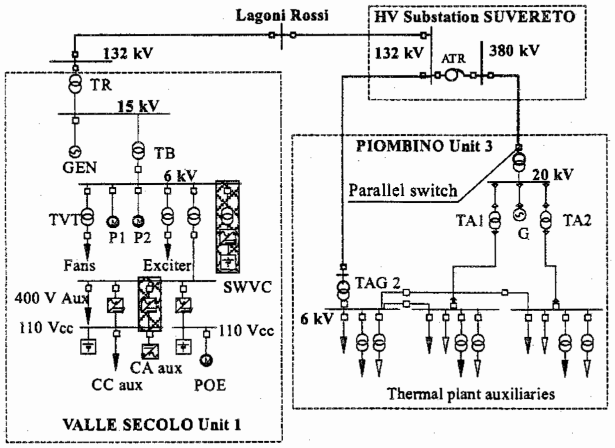

Fig. 1. Scheme of the thermal and geothermal plant

Fig. 2 and Fig. 3 show the results of two simulations: the first refers to the case of a generation-load power mismatch causing a descending frequency rate of 1 Hz/s and the second to the case of a progressive, long term voltage decay at the HV bus of the geothermal plant. At 1.2 s in the first case and at 75 s in the second simulation, the electrical auxiliaries' system of the geothermal plant is islanded and fed by the SWVC.

The SWVC action aims to separate and feed the auxiliaries thus avoiding that the supply disturbance may cause the trip of the group. The generator may therefore remain in operation, co-operating with the grid to face the disturbance, until the intervention of a protection. In the case of Fig. 2, such a protection is an under-frequency relay, and, in the case of Fig. 3, it is a protection for low voltage or for excessive temperature of the condensing water (due to temporarily out of service of refrigerating fans). Then, the unit is disconnected from the network, through a load rejection maneuver.

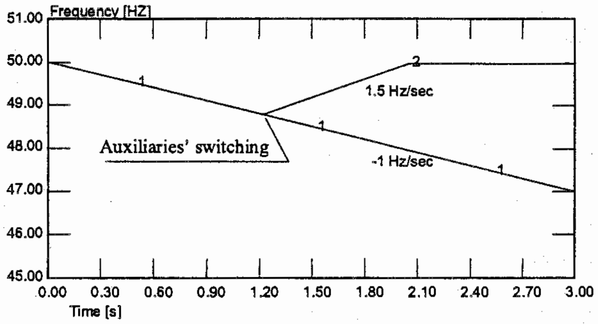

Figure 2. System (1) and auxiliaries frequency (2) during a system frequency collapse

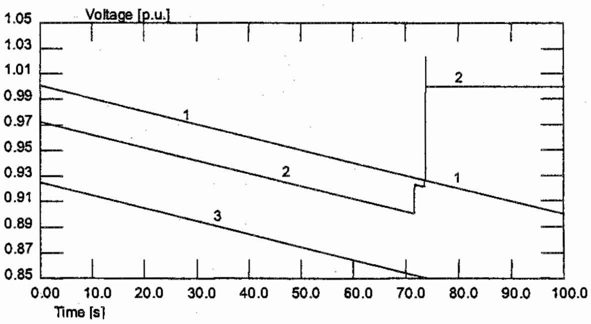

Figure 3. Generator (1), auxiliaries (2) and grid (3) voltages during a system voltage collapse

If the load rejection maneuver fails and the plant trips, the SWVC can startup the electrical auxiliaries of the geothermal power plant, and, in particular, the condenser extraction pump at variable frequency.

The following phases of the restoration maneuver consist in energizing the lines and transformers that connect the geothermal power plant to the Piombino steam power plant and in starting up its electrical auxiliaries. The critical points of the maneuver can be identified in the high value of the inrush currents of the 75 MVA unit transformer (TR) and of the 250 MVA substation autotransformer (ATR) and in the high rating of some induction motors of the steam group auxiliaries system.

Fig. 4 shows the behavior of the current at the generator of the geothermal power plant during the energisation of the lines and transformers TR and ATR. Fig. 5 shows the voltage behavior at the busses of the two power plants, during the startup of three of the motors of the auxiliaries' system of the steam power plant. The current and voltage transients result to be compatible with the settings of the power plant and network protections.

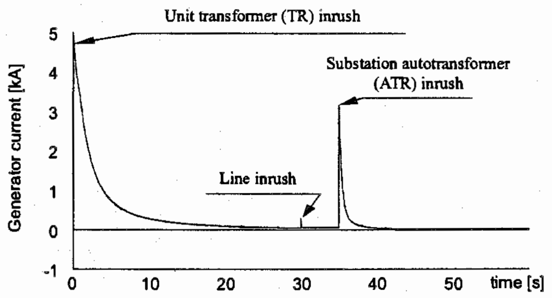

Fig. 4. Energisation of the path to the thermal plant: current supplied by the Valle Secolo generator.

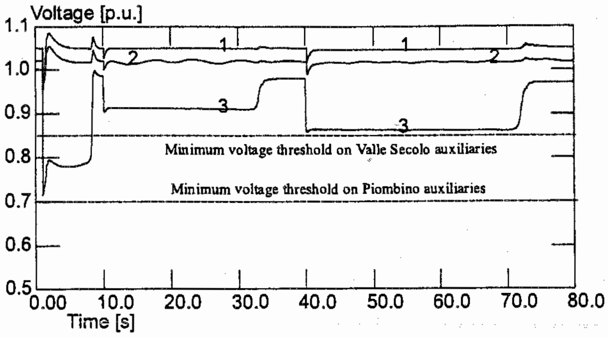

Fig. 5. Startup of three induction motors of the auxiliaries of Piombino steam power plant, namely a feeding water pump of 6.5 MW, and two fans of 1.9 MW and 3.1 MW. Voltage profiles: 1) at Valle Secolo generator, 2) at Valle Secolo auxiliaries' bus, 3) at Piombino auxiliaries' bus.

After the synchronization of the generator of the steam power plant, the two groups will co-operate to allow the steam power plant to reach its technical minimum load of 110 MW. In this phase at every load pick up, the steam power plant participates with the geothermal plant to the frequency regulation and the load is initially shared between the two plants. However, in the following seconds, as shown in Fig. 6, the governor of the geothermal power plant increases the output of its generator, satisfying in this way the total ballast load demand. The steam group can therefore perform its predefined loading ramp at 2 MW/min.

In this conditions, a 20 MW load pick-up gives rise to a transient that has been verified to be compatible with the requirements of the steam power group [5].

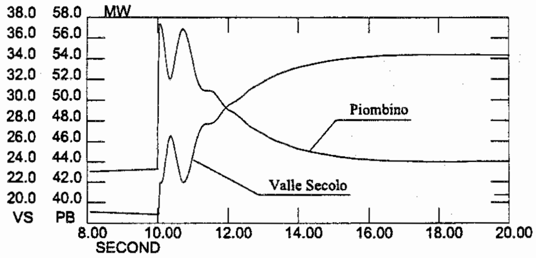

Fig. 6. Power sharing between the plants during the energisation of a load.

3.2 *Thermoelectric steam power plants repowered with a gas turbine*

As already mentioned, some studies have been carried out in the past [6,7] for assessing the possible contribution to the restoration plan from the conventional steam thermoelectric units.

First of all, for all the ENEL units with once-through boilers, a specific load rejection procedure has been developed, tested and used in several occasions. The procedure consists of tripping all fuel to the boiler without tripping the turbine, switching the boiler to the startup and bypass circuit, and then re-firing it after a certain period of time (up to 30 min) during which the house load is maintained on the energy and mass stored in the boiler [8] [1]. Only a limited number of attempts are allowed to perform new ignition, which in case of failure force the unit to a cold restart because of inadmissible thermodynamic conditions.

If the complete load rejection process is successfully accomplished, the thermal unit can remain in operation feeding a restored island of the network, but its chance to autonomously collect load still remains questionable, since it strongly depends on prime mover specific characteristics. The results of the tests reported in [6,7] show that even when these units have successfully completed the load rejection maneuver and have been successfully islanded on their own auxiliaries, they should pick-up load after their synchronization with other units, in order to reduce the probability of tripping on under frequency.

This is supported by a study recently carried out with the aid of an engineering simulator of a 320 MW steam group equipped by a once-through universal pressure (UP) boiler [9]. During the black-start manoeuvre the most important transient phenomena regard the boiler dynamics. A simplified steam section model is adopted by taking into account the mass and momentum conservation equations as well as pressure regulation dynamics. Temperature regulation effects, instead, have been neglected, as they involve time constants much greater than those relevant to pressure dynamics, as shown by the results obtained by using the more detailed simulator. The model of the electrical system of the power plant is conceived to reproduce the slow electromechanical transient phenomena. Faster dynamic phenomena such as electric and magnetic transients due to overvoltages have been disregarded. The presence of the voltage regulators, including the generators capability curves, is also considered. The results of the simulations show that the steam section, when feeding its auxiliary systems, can overcome the frequency transient due to ballast loads connection, provided that the load power is lower than 18 MW. The main reason for the maneuver failure is the fall of the throttle pressure due to the speed regulation that opens the admission valve. Fig. 7 shows the results of the simulation of the failing of a 30 MW load pickup. As shown in Fig. 7, the critical condition for the steam turbine occurs when the admission valve is fully open and the steam pressure is coming down so the mechanical power decreases. Being the mechanical torque balance negative, the frequency drops rapidly causing turbine trip.

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[1] For the case of oil fired drum boilers, it is also possible to operate by keeping burners in service. In case of failure of such a maneuver, the process can continue, after the boiler trip, relying on stored energy and mass. For drum boilers burning coal or natural gas, it is preferable to trip the fuel from the beginning [8].

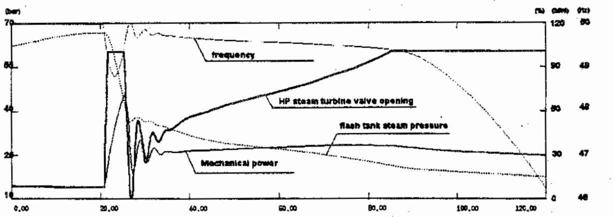


Fig. 7. Simulation of the pick-up of a load of 30 MW by a 320 MW thermoelectric unit (adapted from [9]).

During the last ten years, some ENEL thermal power stations, most of which consist of 320 MW steam turbine units equipped with once-through UP boilers, have been repowered in combined-cycle. The repowering technique adopted by ENEL consists in topping the existing steam sections with a 120 MW gas turbine and recovering heat from the gas turbine exhaust flow by means of an exchanger, which substitutes part of the high-pressure feed-water heaters [11].

An electrodiesel generator is able to feed the auxiliaries of the gas turbines in order to perform the start-up maneuver, and the gas turbine can, in turn, start the auxiliaries of the steam group. This is made easier, in the combined cycle power plants of the Italian Utility, by the presence of the bypass valve that diverts the gas turbine exhaust flow from the exchanger, making the two sections (gas and steam) completely independent in this phase. The presence of a gas turbine section justifies, therefore, further investigations on the black startup capabilities of these repowered stations. In the simulator, the gas section model considers essentially the speed and load regulation, fuel feeding combustor and air compression dynamics. The speed control system also includes a local frequency integrator (LFI) correcting the gas turbine load demand in order to reduce the frequency error to 0.1 Hz. This FLI intervenes when the frequency error exceeds 0.3 Hz or when the turbine power output changes too rapidly.

As earlier mentioned, one of the most critical problems during the restoration of a power system is the frequency control. It is necessary to avoid that load energisation transients cause significant frequency degradation such to involve generators' protections intervention. In case the gas turbine and steam thermal unit perform contemporarily the restoration maneuver, the two relevant frequency regulators must be suitably coordinated. As a matter of fact, the gas turbine is able to control the frequency error without significant delays, while the behavior of the steam unit depends on the thermal inertia of the boiler, very high at low load. This can impair the black-startup maneuver, and, therefore, as illustrated in [10], a load scheduler has been designed and implemented in an engineering simulator of an ENEL repowered thermoelectric plant. The basic function of the load scheduler is to maintain the gas turbine load as low as possible, in order to make it sustaining the whole frequency transient caused by the energisation of ballast loads. Only after the end of the frequency transients and if the boiler pressure is high enough, the load scheduler increases progressively the load request to the SPP section, contemporarily unloading the GT. Another important role of the load scheduler is to provide the appropriate moment for connecting additional loads, taking into account both the gas turbine power output level and the steam unit conditions.

The behavior of this load scheduler is illustrated by Fig. 8, in which the simulation of the pick-up of several loads is shown. During every load pick-up, the steam section participates with the gas turbine to the frequency regulation only during the first seconds. In the subsequent minutes the frequency local integrator controller increases the fuel request of the gas turbine, satisfying in this way the total load demand. For this reason, the steam turbine does not increase its power, saving steam production in the boiler. When the pressure attains the 80% of its nominal value and the frequency error is less than 0.1 Hz, the load scheduler progressively discharges the gas turbine and increases the load request of the steam turbine. This maneuver is performed at 2 MW/min slope. This simulation shows that the steam section reaches in 50 min its minimum-operating load of 110 MW.

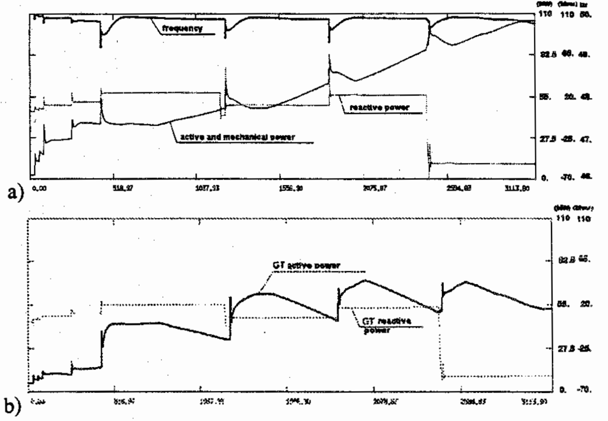


Fig. 8. Simulation of the pick-up of several loads by a 320 MW thermoelectric unit repowered with a 120 MW gas turbine: a) steam section outputs, b) gas turbine outputs. (adapted from [9]).

3.3 *Industrial power plants and combined heat and power generating systems*

In vertical integrated utilities, black-start capabilities of independent power producers (IPPs) were not taken into account, as well as those of embedded generation.

In the present open access environment, the use of combined heat and power plants of IPPs, usually located within or in proximity of industrial areas, as black start sources seems very promising.

The related positive aspects are equally significant for both the transmission manager and the power producer. The former benefits of the possibility of rapidly supplying adjacent, otherwise lost, consumers and the electrical auxiliaries of thermal power plants, not provided with black start resources. The latter can continue producing the steam required by industrial thermal loads, as well as it can achieve a profit by providing the black startup ancillary service.

It must be pointed out that blackouts represent a relevant damage to most of the IPP, worsened by the associated industrial process, to be evaluated according to outage duration and prime mover nature. In general terms we can distinguish between generators whose production is used for internal consumption (autoproducers) and generators whose production is mainly directed towards the electricity market. For the former producers, damage consists in a reduced quality of service, since the industrial power system is islanded from the transmission grid, thus lacking of spinning reserve and regulation facilities. In addition, these kinds of producers are penalized for not selling overproduction to the transmission power system or to other customers. The latter producers have the loss of missing the chance of selling energy and coercion to additional charges in abrupt shutdown and subsequent restart.

In the case of combined heat and power generating system losses due to blackouts may be significant greater because, if the electric service fails to be recovered in short times, the heat production, feeding the industrial process, usually trips, with consequent losses of industrial production.

Investments in black startup resources can be therefore economically justified. Technical details are however highly dependent from the actual layout of the industrial power plant.

4 Guidelines for operator aid and training for power system restoration in open access environment

After the detection of a blackout condition, presumably partial in probabilistic terms, in the relevant area, one can identify busses with null voltage, as well as surviving busbars where some thermal units are performing the load rejection maneuver.

The operator has then the option to reenergize the disconnected regions by black start generation, or can prefer to wait for load rejection to succeed, or at least to profit of available surviving subnetworks, created according to defense plan strategies.

The developed investigation is aimed at determining, before starting the effective restoration, the convenience of each choice with respect to the others, in order to minimize disconnection times as well as to maximize recovered loads. With regard to this point, it must be noted that time and load evolve in a "discrete" way, the former being linked to the maneuver execution time, the latter being available in form of (hopefully several) fraction parts.

To successfully accomplish the restoration procedures, one must account for the multiple phenomena involved in service recovery, extensively presented and quantified in the literature on the subject [12, 13].

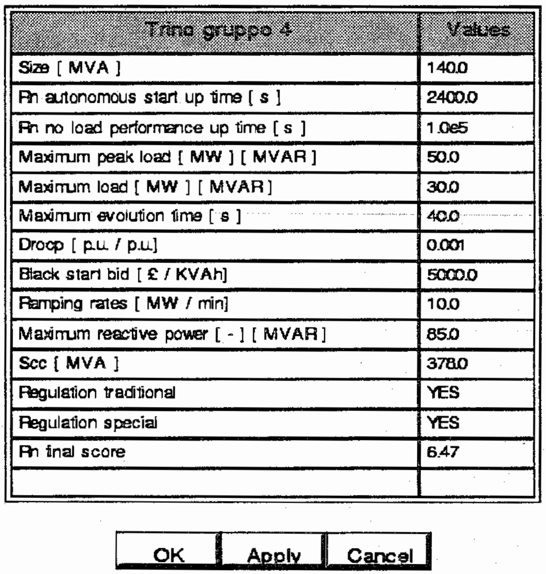
Therefore, each potential restoration source, including both early restoration plants and border busses of surviving networks, is qualified assigning a specific merit index, according to the following attributes.

- Size: it constitutes a significant attribute, in that it enables load acquisition and real power transfer after the synchronization of major thermal units with reduced black-start capacity. Units of large size are of course to be preferred; concerning the restoration capabilities at border busses of surviving networks, they are to be evaluated as shown in the Appendix.
- Autonomous start up: it expresses the chance of the power unit to perform start up procedures without electric energy supply from external sources, typical condition during black outs. Several types of electric power plant may, in principle, be started in autonomous way if equipped with adequate black-start devices [4, 9]; nevertheless, required power levels and energy amounts strongly reduce practical application of relevant technologies in many cases. Merit should be given to units requiring limited time in performing the whole startup process. In this respect the busses at the borders of surviving networks are immediately available.
- No load performance: the unit, after being successfully black started up or after completion of the load rejection procedure, should operate stable on its auxiliaries or on an load island, until the ISO provides the possibility to synchronize such a unit with a recovered area equipped with sufficient base load. Most units safely operate for significant time in such conditions.
- Energisation capacity: the restoration source is called to reenergize disconnected connections such as step-up and step-down transformers, as well as overhead lines or cables. Phenomena like harmonic resonance, ferroresonance or transformer in-rush currents must be accounted for, also taking into account component non linearities and evolving topology. Capacitive loads are to be compared with reactive power capabilities of committed early restoration units. Both units and surviving network terminals show better performances if characterized by high values of short circuit power.
- Cold load pick up response: the restoration source must be stable while pinking up load blocks of expected size. However, according to the load nature [7], real and reactive power overshoots are frequent, so that the actual dynamic behavior of the system is often worse than the expected one. This is strongly related to regulation device characteristics and unit inertia time constant, finally affecting the choice in load reconnection priorities. Each unit should be characterized by the load amount that can be energized with sufficient quality of service.
- Regulation capacity: separated operation, including stable load energisation, often requires specific regulation devices. Italian defense and restoration plans, with regard to generation sources, are based on specific devices available at hydro and fossil units. Indicators like speed governor

permanent droop and automatic voltage regulator (AVR) gain may be used to rank the units according to performance in restoring the network. For the case of surviving areas, some procedures to infer equivalent indicators are described in the Appendix.

- Generation ramping rates: each early restoration source is characterized by some constraints that limit prompt load energisation. These constraints are typically related to the involved prime mover.
- Price of the black-start services: each black start unit contributes to the restoration plan if it has a contract with the ISO that settles the price of the black-start services. In the case of a blackout, units with lower prices will be preferred to the others in order to restore the network.

The merit index used to sort the available restoration resources is the balanced summation of the values given to the above-mentioned attributes, each adequately normalized. Figure 9 presents an example of merit index generation by an expert system prototype in the case of a group of Trino combined cycle power plant, located in the north-western part of the Italian transmission grid.



Trino gruppo 4	Values
Size [MVA]	140.0
Rn autonomous start up time [s]	2400.0
Rn no load performance up time [s]	1.0e5
Maximum peak load [MW] [MVAR]	50.0
Maximum load [MW] [MVAR]	30.0
Maximum evolution time [s]	40.0
Droop [p.u. / p.u.]	0.001
Black start bid [£ / KVAh]	5000.0
Ramping rates [MW / min]	10.0
Maximum reactive power [-] [MVAR]	85.0
Scc [MVA]	378.0
Regulation traditional	YES
Regulation special	YES
Rn final score	6.47

Fig. 9. Merit index generation for an Italian unit.

Procedures are generated to classify all the units and surviving zones terminals connected with EHV network, generating the merit indices and detecting the most appropriate restoration sources.

The average merit index acts as a threshold, splitting the sources list into two parts, the former including units that are candidate to recover the network, the latter presenting remaining generators to be considered as preferential targets in power system restoration.

Attention must be also given to subtransmission islands: they include ballast load, necessary to avoid excessive overvoltages while energizing EHV lines, as well as for providing base power for parallel operation of large UP thermal units. In addition to this, they could contain minor units, as well embedded generation, useful to improve size and performance of the grid island under construction.

A parallel classification of target busses giving access to subtransmission network should be performed, according to the following items:

- Size: it refers to all the reachable loads within the island, considering the chance of reenergizing users from different access busses. Procedures should be introduced to manage an initial split of the loads between the terminals and a following redistribution of them after each commitment.
- Included generation: small units may be involved in restoration process while recovering ballast loads. Merit should be given to subtransmission islands presenting extended embedded resources.
- Load fractions and nature: extreme attention must be given to the chance of reconnecting load in a progressive way, so that each load should be characterized in the same way as the attribute of cold load pick-up was defined for generating units. Significant additional information will regard load type, in order to distinguish between static loads, asynchronous motors, thermostatically controlled or driving time-varying mechanical loads [7].
- Load distribution: within a subtransmission island, preference should be given to loads close to access node, to reduce overall restoration time. Indices like load momentum with respect to the access node could be adopted to drive restoration maneuvers.
- Load priority: it forces the restoration process to be directed towards users showing high social impact, being these ones the same to be last disconnected after the failure of the defense plan.
- Ballast load bid: the provision of restoration ancillary services is quoted according to specific clauses in contractual agreements between ISO and distribution companies.

As a result of the complete node classification, the operator will be shown, or at least made aware of the expert system decisions about, sorted lists of sources and target busses.

The coupling procedure to start parallel restoration processes requires the following steps:

- a decisional criterion to join together sources and target busses, being usually the minimum electrical length or the minimum number of breaker operations.
- A contemporary check for mutual compatibility between the attributes of sources and target busses (for example, sufficient size of sources with regard to the load of the subtransmission island or to the base load of thermal units).
- The consideration for additional constraints, such as, for example, the suggestion of reducing the number of involved

transformers.

After developing the coupling procedure, which of course could leave some sources or targets uncommitted, the expert decision-support system does not provide restoration path in the conventional way.

First of all, out of service components, as well as operation failures, are accounted for, and the coupling procedure is restarted at any unforeseen occurrence.

Moreover, whenever a black start-up unit and the relevant step-up transformer successfully reenergize an EHV line, this recovered subsystem becomes a surviving network, with modified intrinsic characteristics with regard to the attributes that affect the merit index of sources.

According to this fact, each single operation should restart the classification procedure, therefore assuring complete system flexibility, but decelerating the decisional process. To this regard, an acceptable compromise would probably be the resorting of restoration sources only whenever a subtransmission island is accessed, or a new generating unit is synchronized to the recovered subsystem.

To test the proposed strategy, an expert prototype is being realized according to presented procedures; the following paragraph will briefly describe its architecture.

5 Outlines of an Associated Expert System Prototype

In a previous analysis [14], concerning an expert system prototype for power system restoration in a vertically integrated utility, complete detail of the construction of a restoration path was presented, integrating a knowledge development environment with an internal simulator. In fact, such a prototype is set-up by an expert system and a real time power system dynamic simulator. The restoration process is driven by the data coming from the simulator that describes the dynamic behavior of the reintegrating system and substitutes the SCADA system.

Modifications towards the present electric market structure, as well as the need for including dynamic phenomena evolving through very different time frames, suggest the use of more powerful codes for dynamic analysis along several terms.

The use of external simulators causes the expert system to be more efficient in processing multiple, parallel developing, scenarios. Even if reasonable, such a choice must account for the usual difficulty of treating with a continuously increasing network.

It has been therefore proposed an intermediate control motor, which manages variations of network topologies, providing a new network to the external simulator, while holding the state variables coming from the previous working scenario.

In other words, while the inference engine generates decisional files, codified in sequences of breaker operations, the control motor for the external simulator starts progressive simulations, with snapshots of significant variables fed back to knowledge development environment.

A limited subset of network variables, available at a predefined scanning rate, constitutes the basis for the expert system, or the operator if an interactive mode is adopted, to verify acceptable values for constrained quantities (frequency and voltage, for example) and empirically determined stability conditions.

The result of such check is the activation of subsequent maneuvers, usually performed after frequency and voltage recovery within safety ranges.

The control motor is in the end designed to accept strategy modifications driven by any new restoration source sorting procedure, considering new operation files coming from the inference engine.

6 Conclusions

The paper regards possible reassessment of power system restoration strategies in a competitive electricity market.

The unbundling and liberalization of the electrical energy systems has justified further investigations on the black-start capabilities of the various types of power plants. Some studies have been recently carried out in Italy for assessing the possible contribution to the restoration plan from thermal units that previously were not considered as black-start sources. The paper summarizes the obtained results relevant to geothermal plants, to steam power plants repowered with gas turbines and to industrial combined heat and power generating plants.

ISO control center operators are asked to decide for best ways to recover from more or less extended blackout conditions, and cannot account on safe management of generation and consumption in extreme emergency condition.

Specific guidelines to dynamically create, and/or modify if more convenient, restoring areas have been here proposed and included in an expert system prototype for both operator assistance in decision making and training purposes.

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Appendix

Definition of equivalent attributes for surviving network terminals:

- Extension: Graphically determined by direct intervention on the test network of the expert system prototype (see Figure 10). In a real application, identified through blackout assessment criteria.
- Size: as a first assumption, assumed equal to the MVA thermal rating of the connections departing from the considered border busses.
- Short circuit capacity: deduced by selected diagonal elements of the surviving network impedance matrix, obtained using LU factorization techniques. Each surviving network extension changes border nodes: admittance network based techniques for networks with increasing nodes may be adopted [14], still ending with LU factorization for new required driving point impedance.
- Inertia time constant and permanent droop: in approximate form, both deduced as weighted average through rated powers of included units, and assumed equal for each surviving grid terminal.

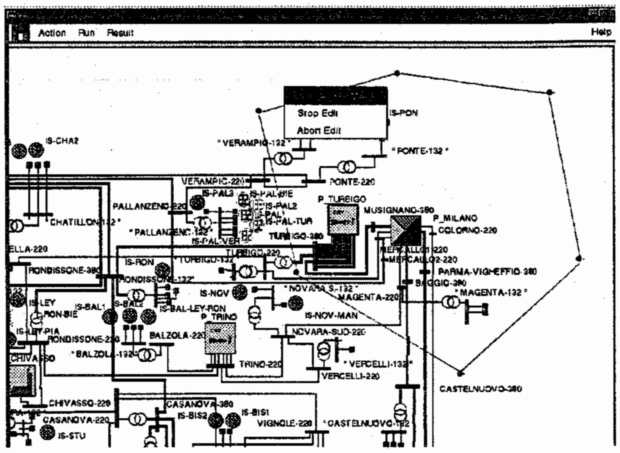

Fig. 10. Graphical set of a surviving grid while testing restoration strategies in an Italian sample transmission network.