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Simulations and Field Tests for Power System Restoration

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Abstract: This paper deals with power system restoration, and points out the importance of performing periodical extended restoration tests. Field tests should be preceded by accurate simulations, whose aim is to check the system operation and predict possible problems, mainly of dynamical nature, that can arise during the most delicate steps of system restoration. This concept is illustrated and discussed by means of a case-study, concerning the recent study and field test, performed in Italy, of a restoration path with novel interesting features. Aiming to evaluate the significance of the information got through preliminary simulations, simulation results are compared with field test recordings. The problems individuated through simulations, and also the main differences between simulation results and field recordings, are reported and commented.

Key-Words- **Power System Restoration, Power Generation Testing, Restoration Path Testing.**

1 Introduction

Power system restoration has greatly raised its importance after the large blackouts that recently took place both in Europe and North America. In some Countries, these large events led the TSOs to issue new restoration plans and more stringent policies concerning power systems security.

Power system restoration after a blackout is a complex matter, which requires in particular to tackle different problems of weak systems dynamics. Field tests are required to check the effectiveness of restoration plans. However, the practical realization of field tests involving relatively wide system areas is often quite difficult. One of the main difficulties related to extended restoration tests lies on the disturbances that can affect customers during these tests. As a consequence, field tests are often limited within power plants, and consist in load rejection tests of thermal groups and black startup tests of early restoration units (usually hydro units).

The recent large events have clearly pointed out that system restoration procedures are often unsteady. When real restoration cannot be accomplished as planned in restoration plans, the whole process can remarkably slow down, increasing security problems, inconveniences and costs in large system areas. This fact suggests to perform periodical restoration tests extended to the whole restoration paths, that are the back-bone of the independent system areas created during parallel system restoration before progressive network meshing.

In Italy, after the September 2003 wide blackout, GRTN (the Italian System Operator) issued a novel defence plan and is at present developing, together with the owners of power plants, new studies aimed to further improve the Italian defence plan. In 2004, GRTN issued a new policy containing prescriptions concerning the power plants involved in the National restoration plan. This document dictates their features and gives indications about the modalities and frequency with which restoration field tests must be performed within power plants and also on whole restoration paths.

In short, concerning black-start units, the new policy states that they must have capability of fast and fully autonomous startup, significant power concentrated on few units, adequate real and reactive power capability in over and underexcitation to get a suitable voltage regulation, and allow proper frequency regulation in isolated operation.

GRTN asks to accomplish periodical field tests on black-start units and to collect the relevant recordings, results and observations to constitute a historical file of the tests performed, so as to allow drawing performance indices relevant to the success rate of black startup tests and to any cause of failure. The maximum time between two black startup tests must not exceed 6 months. Also, at least once every 3 years a black startup test must be accomplished following a unit switch off from a load condition.

In the same way GRTN aims to monitor the load rejection performances of each thermal plant rated more than 200 MVA and of all thermal plants included in the National restoration plan. As for black startup units, GRTN prescribes load rejection tests planning and data recordings. The maximum time between two load rejection tests must not exceed 6 months.

Field tests of whole restoration paths are by far more complex with regard to personnel engagement and coordination, coordinate use of power plants and more or less heavy customers involvement. GRTN periodically plans such drills, which are performed in the most suitable periods considering the operation requirements of the network. These tests have the objective to check the time required by the network preparation, the separation from the network of the involved black startup and thermal units, the operation and regulations performed by the black-start units during the circuit energization and load pick-up, the thermal unit reconnection and load pick-up, the final synchronization between the path and the bulk network. GRTN prescribes that, in order to include a new path in the restoration plan, it must be completely and positively tested on the field.

2 Preliminary simulations

Power system restoration subsequent to a massive blackout is a very complex problem that requires to face different dynamic phenomena like generators electromechanical stability, voltage stability, frequency regulation, re-synchronization of independent subsystems. Most of these phenomena need to be evaluated during the reconstruction of restoration paths, in correspondence to the most critical phases like ballast load connection, energization of long HV lines, connection and load pick-up of thermal units.
In the nineties, power system engineers developed specific simulation environments and accurate models to simulate dynamics in complex networks, where the problems found during power system restoration can be included [1-4]. The process has been the following: data obtained from restoration field tests have been used to tune proper models, with the aim to provide tools that could allow accurate and reliable preliminary simulations.
Today this process is mature, and sophisticated network simulators are available with which all the different phases of system restoration can be simulated with sufficient accuracy. Simulations are now a fundamental analysis tool to design new restoration paths or change existing ones, check the correct operation of restoration paths in case of changes of the involved quantities (for example the amount of ballast load), individuate alternative solutions for existing restoration paths to be prepared to face with components unavailability, and so on. Simulations allow choosing proper parameter settings, and individuating possible problems like excessive electromechanical or frequency transients or unwanted protections intervention, that can occur mainly during restoration paths energization and load pickup, when the power system is weak and exposed to the possibility of a new collapse. Furthermore, simulations are indispensable to provide power system engineers with indications relevant to those restoration phases for which there is a lack of experimental data, due to the obvious difficulty to perform restoration tests involving very large parts of the network. An example is the process of progressive network meshing subsequent to the restoration paths energization and local load pick-up.
The first simulation phase concerns a steady-state analysis. These first simulations allow to check the restoration feasibility considering only steady-state requirements (i.e. conformity with the generators capability limits, real and reactive power balance, load pick-up of the thermal unit(s)), and to individuate proper voltage settings along the restoration circuit.
Once that this first phase is successfully completed, it is necessary to deepen the analysis through simulations capable to provide indications concerning the dynamics of the restoration. Of course, this second simulation phase is much more difficult and requires proper simulation tools and accurate models. In the following Sections, in order to allow evaluation of the simulation results and to compare them with field test recordings, reference is made to the field test, performed in December 2003, of a new restoration path in Central Italy whose main features are illustrated in Section 3.
Static simulations have been performed by GRTN, while dynamic simulations have been performed by CESI (Centro Elettrotecnico Sperimentale Italiano) by means of a power system simulator consisting in a simulation environment in the time domain suitable for dynamic security studies and for the solution of various control problems. The power system simulator used is not suitable to investigate electrical transients, but it can analyse electromechanical transients (Short Term Dynamics) and dynamic phenomena evolving on medium and long term (Long Term Dynamics) like small perturbations stability, units loss of synchronism or network areas separation, transient overloads and distance protections trips, voltage collapse, effect of emergency control actions like fast-valving, load-shedding, and so on.

3 Description of the new restoration path

GRTN - Regional Control Centre of Roma designed, simulated and tested a new restoration path [5,6]. The new path was needed to replace an old one, because of a long programmed unavailability of its black-start units. The new path, illustrated in Fig. 1, includes only one early restoration unit (unit 6 located at the S. Giacomo hydro plant) and concerns a small number of power plants and electrical stations: the S. Giacomo 380 kV and 220 kV sections, the Provvidenza 220 kV pumped storage plant, the 220 kV and 380 kV sections of the Villavalle station, the Montalto 380 kV station and the nearby Montalto thermal plant. A small number of plants and stations simplifies the switching procedure, shortens the network preparation, and results in lower possibility of wrong maneuvering and less time for the whole path restoration.
Unit 6 is rated 310 MVA, 12.5 kV, with a 280 MW Pelton turbine (this is at present the largest Pelton group in Italy). The Provvidenza pumped storage plant includes three units. Unit 2 (52 MVA, 15 kV, separate pump and turbine) and unit 3 (65 MVA, 15 kV, reversible) are those selected to load the path. In motor operation units 2 and 3 absorb respectively about 50 MW and 54 MW.
The lines included in the restoration circuit are:

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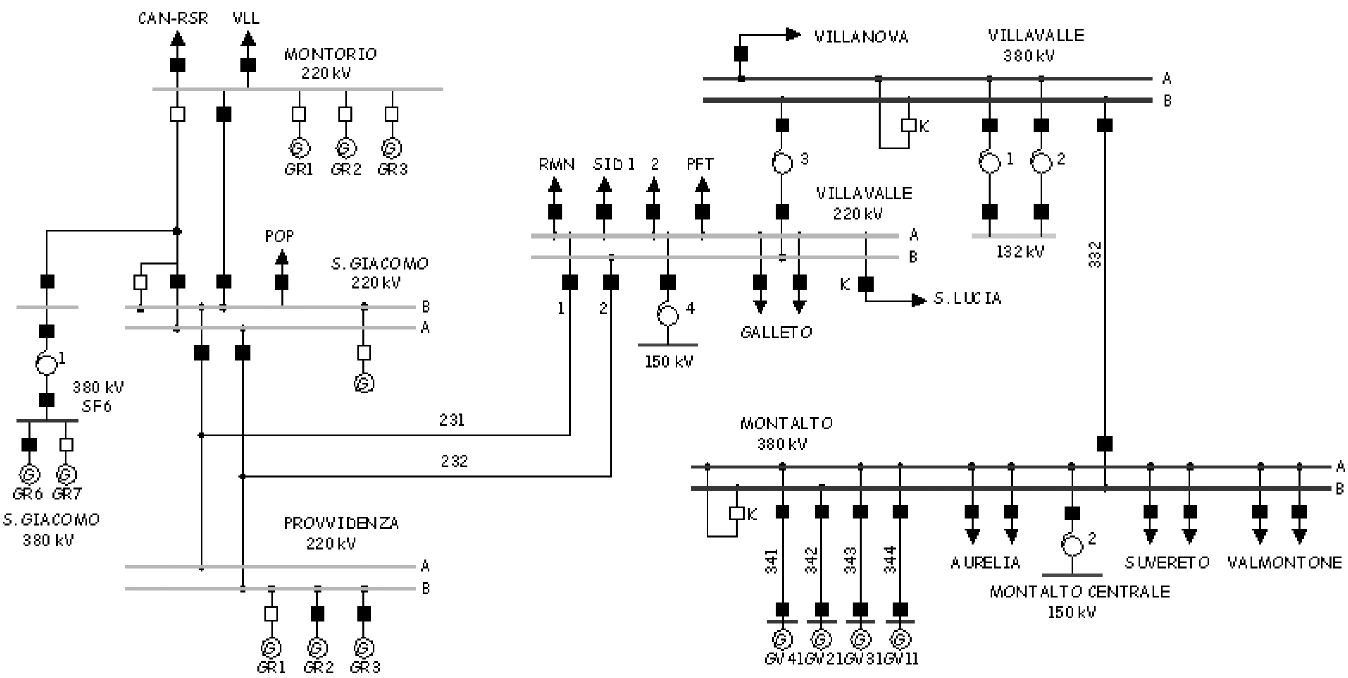

Fig. 1. One-line scheme of the new restoration path (black squares indicate closed breakers, white squares indicate open breakers)

- 220 kV S. Giacomo-Montorio, 15 km
- 220 kV S. Giacomo-Provvidenza-Villavalle, 82 km
- 380 kV Villavalle-Montalto station, 111 km
- 380 kV Montalto station-Montalto plant, 6 km.

The new path has an interesting innovative feature, studied to overcome some of the problems found after the 2003 blackout: the ballast load required during the circuit energization is given by two units (in motor operation) of the Provvidenza pumped storage plant, instead of blocks of distribution loads. This solution, exploiting also the double bar configuration of the electrical stations, allows the complete separation of the restoration path from the subtransmission and distribution networks, so as to avoid any disturbance to customers during restoration field tests.
Moreover, a second very interesting aspect connected to the use of pumped storage plants as ballast loads is their fixed and known amount, which improves the reliability of a real restoration. In fact, traditional procedures require connecting distribution loads, so that the load available on each restoration path depends on the daily load diagram and is also subject to the uncertainty of cold load pickup [1,4].
Since restoration plans are typically developed accounting for the maximum load conditions, their effectiveness tends to decrease if the blackout occurs during a low load condition. Exemplary is the large Italian blackout occurred on September 2003, early on Sunday morning. In the area of Rome, due to the unavailability of the required load amount, restoration could not be performed as planned, and alternative paths had to be used, taking as a whole a longer time. Conversely, the pumped storage plants provide fixed and known load, and allow performing as planned (if all the involved system components are available) the early and most critical restoration stages at any day-time and independently on the system actual load diagram and on the problem of cold load pick-up.
This is the first restoration path in the Italian grid designed according to this idea.

4 Simulation results and field recordings

All Simulations Results (SR) reported refer to a common pattern: at t=0, unit 6 is operating at no-load with reference voltage equal to 11 kV and energizing the restoration circuit from S. Giacomo to the 220 kV Villavalle station; the two pumps are connected respectively at t=1 s and t=20 s; the long 380 kV line Villavalle-Montalto is energized at t=40 s.
Simulations have been carried out considering different restoration sceneries. Effects of the pumps connection have been evaluated assuming either a ramp connection (lasting 10 s, with about 5 MW/s power gradient) or a step one. The voltage settings have been chosen so that to allow a suitable reactive power balance, still complying with the capability limits and keeping an acceptable voltage level at the power stations involved.
The ramp connection of the pumps, illustrated in Fig. 2, corresponds to the gradual turning off of the pumps starting units, while the step connection (Fig. 3) corresponds to their instantaneous removal. The last case is kept as a reference to check the electromechanical stability of the isolated system composed by the black-start unit and the two pumps. Power system stabilizers (PSS) have been considered either on all the three units, or only on the black-start unit (the largest one), or on no one. SR reported in Fig. 3 shows stable power transients.

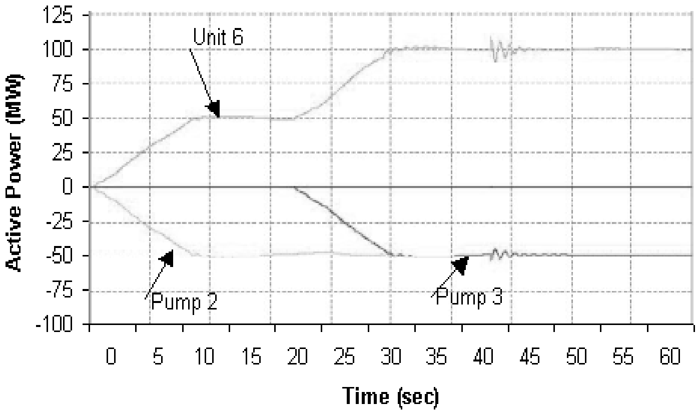

Fig. 2. SR: unit 6 real power (for ramp connection of the pumps)

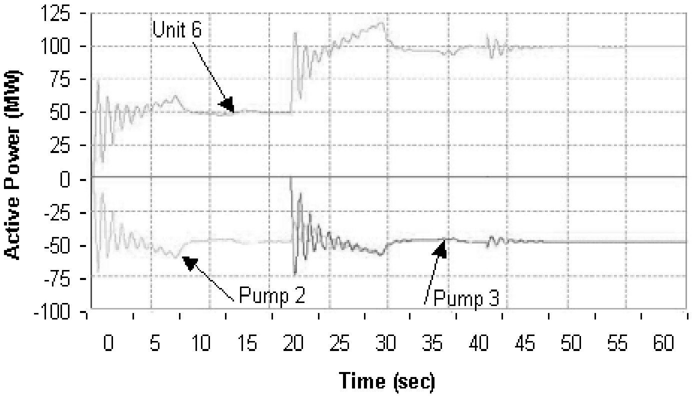

Fig. 3. SR: unit 6 real power (pumps step-connected and PSS on unit 6)

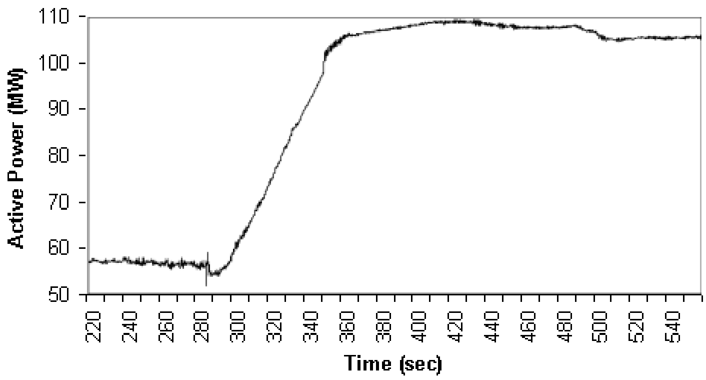

Fig. 4.1. FT: Detail unit 6 real power at the second pump connection

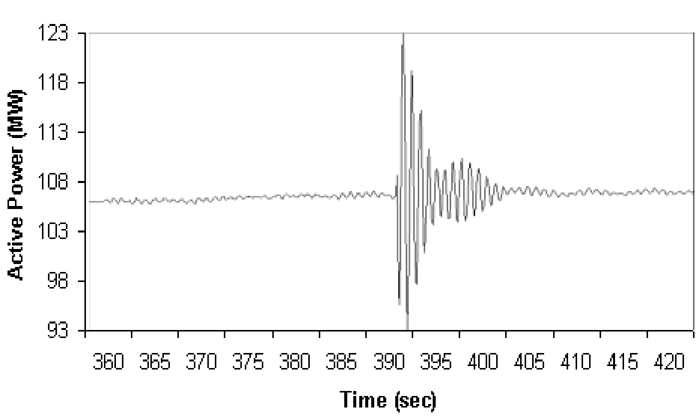

Fig. 4.2. FT: unit 6 detail real power at the line VLV-MLT connection

Fig. 2 shows that the pumps connection do not cause significant electromechanical obscillations of unit 6, but the energization of the line Villavalle-Montalto originates greater obscillations, which are however damped by the PSS on unit 6. The PSS are activated when the unit's minimum real power threshold (0.3 p.u.) is reached: in Fig. 2 this happens at about t=28 s. SR pointed out that the PSS activation causes a voltage step-down in unit 6 and (damped) voltage obscillations along the path, while the PSS exclusion leads to lower, but less damped, voltage obscillations. However, this behavior didn't lead to exclude the PSS, because of their positive effect in damping the voltage transient at the energization of the line Villavalle-Montalto (t=40 s, see Fig. 5.1).

During the Field Test (FT), the first pump has been connected in two stages, therefore a direct comparison with SR cannot be made. However, during FT the power gradient has been lower (around 2 MW/sec) than that assumed for simulations. Unit 6 real power at the second pump connection (about 1 MW/s) is shown in Fig. 4.1, which is very similar to SR of Fig. 2. Of course, the higher power gradient used for the preliminary simulations allow a prudential evaluation of the relevant transients.

The simulation sceneries used to investigate voltage stability concern the ramp connection of the pumps, while the voltage settings have been chosen so that to keep all units either away from, or at, their underexcitation limit. Simulation results point out the absolute need to avoid the contemporary operation of all units at their underexcitation limit, in order to avoid a not controllable voltage raising trend due to the interaction among their voltage regulators that can cause slow reactive power swings [7]. This situation is shown in Fig 5.2, where power transients are stable until the connection of the line Villavalle-Montalto. After this moment a not controllable voltage-raising trend (voltage instability) takes place. Therefore, to avoid voltage instability, at least the prevailing unit (unit 6) must be kept away from its underexcitation limit. In this case, according to simulations (Fig. 5.1), the voltage transients of the three units do not exhibit particular problems.

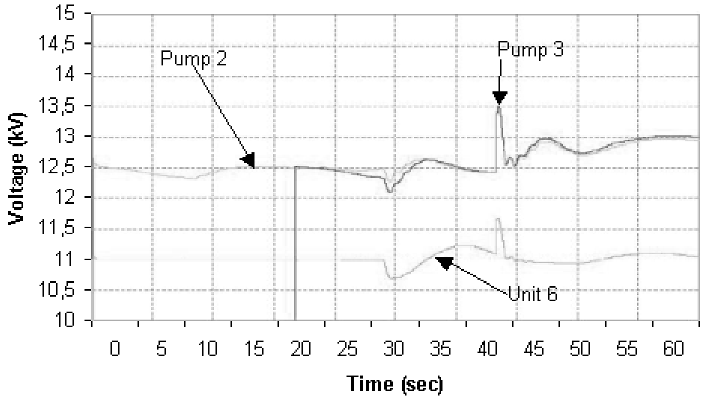

Fig. 5.1 SR: unit voltages (PSS on unit 6, unit 6 not operating at its underexcitation limit)

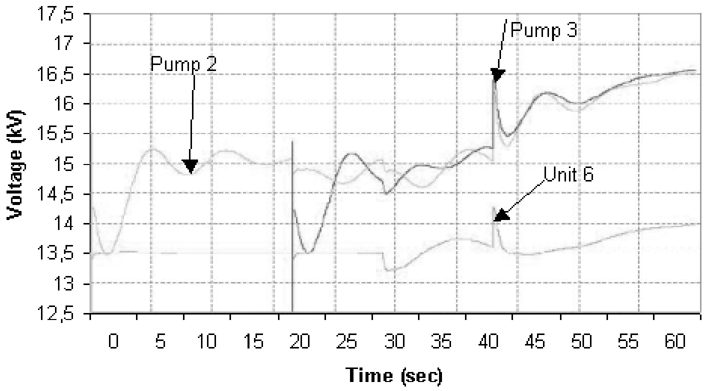

Fig. 5.2. SR: voltage instability with all units operating at their underexcitation limit (initial voltage set at 13.5 kV for all units)

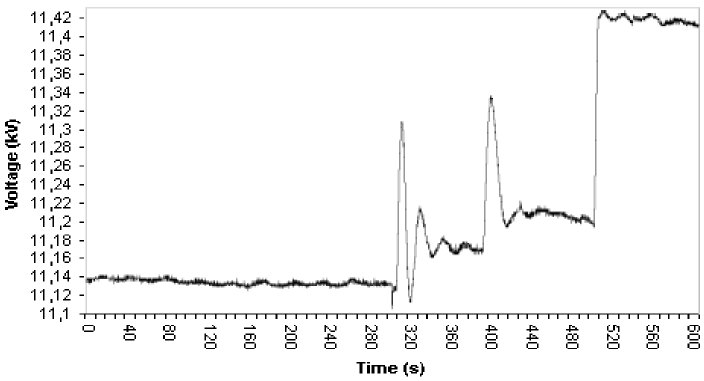

Fig. 6.1. FT: unit 6 voltage at the first pump connection

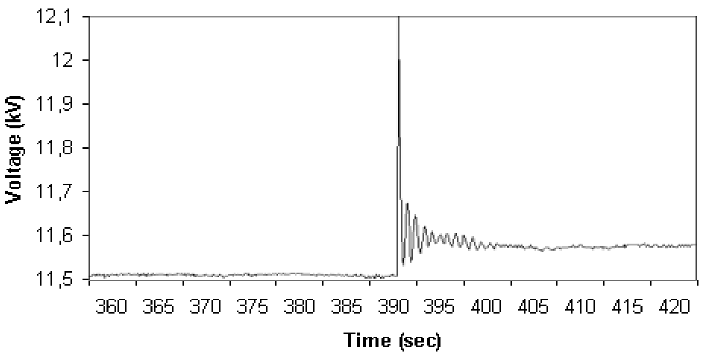

Fig. 6.2. FT: unit 6 voltage at the line Villavalle-Montalto energization

In Fig. 5.1 the main voltage peaks correspond to the PSS activation and to the energization of the line Villavalle-Montalto. However, voltages along the restoration circuit are properly limited, and the capacitive power of the 380 kV line (about 60 MVAr) is partly compensated by the reactive power consumed on the 380/220 kV transformer at S. Giacomo after the ballast load connection, while the rest is absorbed by unit 6 in underexcitation (Fig.s 7, 8).

The difference in unit 6 reactive power between SR and FT is mainly due to the voltage increase required at Provvidenza, where the low voltage level led to exceed the unit 3 rated current. This problem could not be solved through a local voltage regulation, therefore the excitation of unit 6 was somewhat raised (Fig. 6.1, t~500 s), increasing so the reactive power generated by the HV circuit before the energization of the line Villavalle-Montalto. The consequence was to increase the reactive power absorbed by unit 6 after the connection of this line, nearing more but not exceeding its under-excitation limit, which was about 80 MVAR in the operative condition of that moment.

Simulations show stable real and reactive power transients and demonstrate the capability of unit 6 to stably operate in underexcitation also if the two pumps at Provvidenza operate at their underexcitation limit.

Considering frequency transients, in agreement with the SR (Fig. 9) that don't point out specific problems, during the FT unit 6 showed a great flexibility and didn't evidence any problem. SR predicted a minimum frequency around 49.05 Hz after the second pump connection, while the maximum recorded under-frequency was 49.1 Hz, corresponding to a 1.8% deviation from the nominal value, after the connection of the first pump, and 49.15 Hz after the connection of the second pump. This difference is due to two main factors: a) the permanent speed droop of unit 6 in isolated operation is reduced to 0.5%; this slows down the frequency control so that the regulation time becomes similar to that required by the secondary control. Therefore, the 19 s assumed in the simulated pattern between the connections of the two pumps are not sufficient to reach a steady condition, while in the FT 10 min elapsed between the two connections; b) as already pointed out, simulations considered higher power gradients than those obtained in the FT.

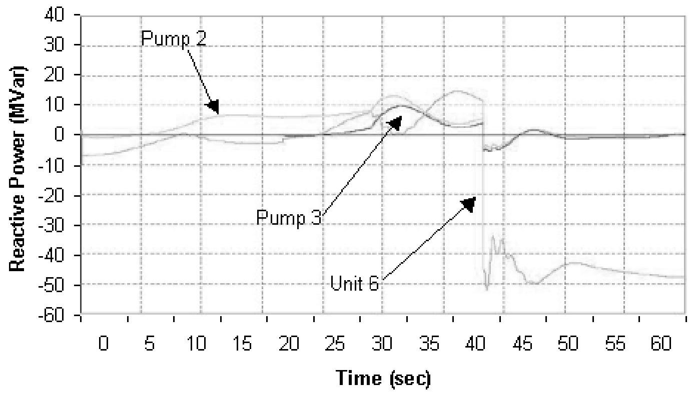

Fig. 7. SR: units reactive power

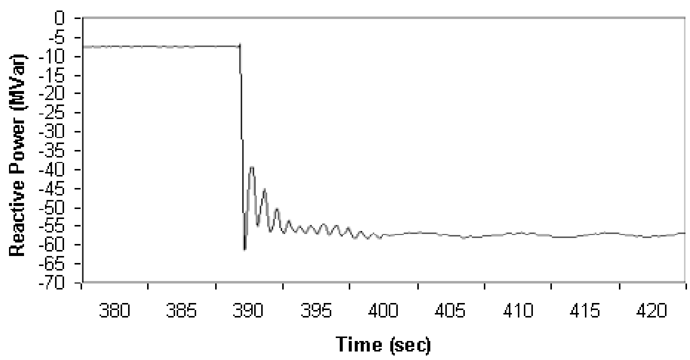

Fig. 8. FT: unit 6 detail reactive power at the line Villavalle-Mon. energization

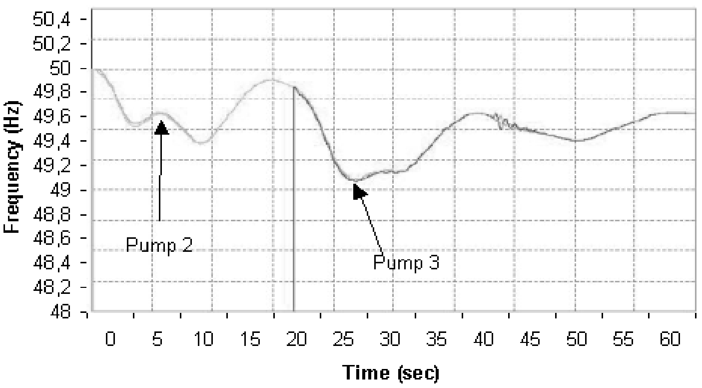

Fig. 9. SR: frequency in the energized circuit

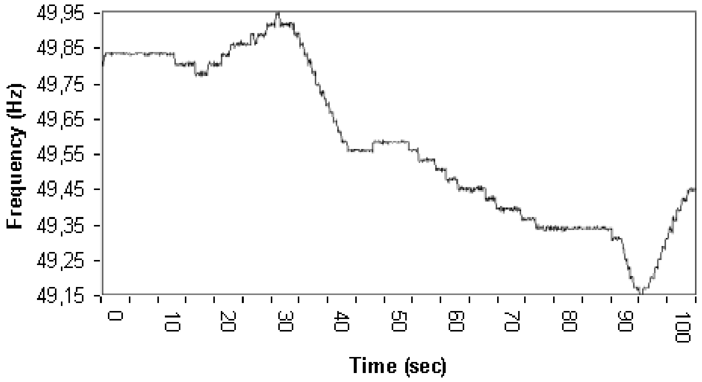

Fig. 10. FT: frequency transient at the second pump connection

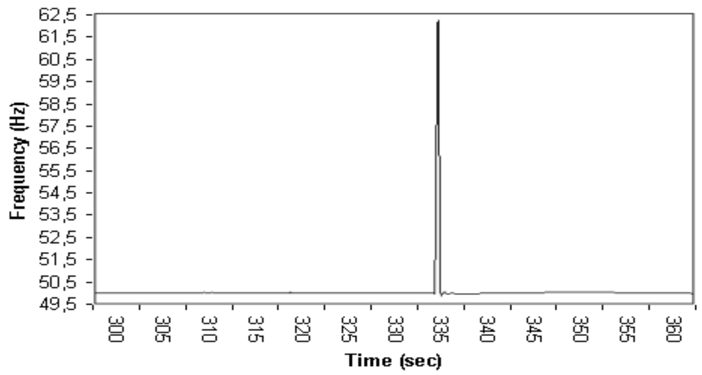

Fig. 11. FT: electrical frequency peak at the connection of the S. Giacomo ATR.

In addition, it must be noted that, aiming to prevent unwanted interventions caused by the frequency transients at the pumps connection, before the FT the minimum frequency and load shedding relays of the units 2 and 3 of Provvidenza were excluded. The exclusion is now permanently adopted to ensure the pumps connection in the event of a real restoration.

Finally, preliminary analysis of the new path allowed individuation of a critical step in the energization of the 400 MVA ATR connecting the 380 kV and 220 kV sections of S. Giacomo (number 1 in Fig. 1). This action causes a significant frequency peak that would cause the intervention of the "speedometer anomaly" protection of the speed governor of unit 6. This protection compares the mechanical frequency, measured on the unit shaft, with the network electrical frequency, measured on the unit bar. Therefore, to avoid the unit stop and the restoration failure (not just for the FT, but also in the event of a real restoration), this protection is now permanently excluded.

Fig. 11 shows the electrical frequency peak (about 62.5 Hz, corresponding to a 25% increase) recorded in the small isolated path at the connection of the ATR.

5 Conclusions

Extended field tests and preliminary simulations should be considered as necessary steps to set up effective restoration plans. Simulations can play a fundamental role in individuating specific problems, mainly of dynamic nature, that can arise during the energization of system areas. The case-study concerned in this paper allows pointing out some of the main problems that can be analyzed through simulations and the usefulness of the indications obtained before field testing. Conversely, the need for any further refinement of the models used can be estimated, after the field tests, comparing simulations and field recordings.

6 Acknowledgements

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