21, rue d'Artois, F-75008 Paris
http://www.cigre.org

14-116

Session 2002

THE ITALY-GREECE HVDC LINK

A.Giorgi, R.Rendina — ENEL-TERNA, Italy
G.Georgantzis — PPC, Greece
C.Marchiori, G.Pazienza — ENELPOWER, Italy
S.Corsi *, C.Pincella, M.Pozzi — CESI, Italy
K.G.Danielsson, H.Jonasson — ABB Utilities, Sweden
A.Orini, R.Grampa — PIRELLI, Italy

SUMMARY

The essential characteristics and the main features of the new Italy-Greece HVDC link (GRITA), whose commissioning was achieved within 2001, are shown. This link, realized by ENEL-TERNA and Public Power Corporation (PPC) with ENELPOWER acting as main contractor and with the engineering support of CESI, was designed and manufactured by ABB and PIRELLI and will be operated according to the prescriptions of Italian and Greek Independent System Operators (ISO). The Italy-Greece HVDC link consists in a mono-polar link with sea return, with a rated voltage of 400 kV, a rated current of 1250 A and a rated power of 500 MW (guaranteed at the inverter side), which can flow in both directions between Galatina (Italy) and Arachthos (Greece). The link is based on a grid commuted twelve pulse thyristor bridge and is already conceived for a possible 1000 MW bipolar extension. Its design is characterized by a state-of-art level of quality and reliability of the overall converter stations equipment (DC cable, thyristor valves, converter transformers, AC and DC filters, smoothing reactors, AC and DC yard switching equipment), as well as by a modern and effective control and protection system (converter firing, pole power control, frequency regulation, inter-station tele-communication, station control and monitoring). The main performances of the Italy-Greece HVDC link, documented during the commissioning tests, will be compared with the system design results to give evidence of the high technical competence and quality of the combined engineering effort provided by all parties involved.

Keywords: HVDC link, technical specification, system design, voltage-current-power-frequency control, DC cable, electrode, protection system, field-factory tests, system performances.

1. INTRODUCTION

GRITA project objectives are: interconnection of the South Italy with Greece, the last EU country outside the Community grid; access to EU grid by new potential electrical energy producers from Greece, Albany and Turkey; significant contribution to the "Mediterranean ring" reinforce, fostering the East-West electrical energy exchanges. **GRITA project waited benefits** for the two interconnected networks are: minimization of grids operation costs and oil consumption; better coordination and use of hydraulic resources; mutual assistance in emergency conditions by increasing the operation reliability through the active power reserve sharing; increase of operation flexibility and energy exchange between Italy and Greece; improved Greece energy transactions with West Europe by production total marginal cost reduction and energy exchange increase. **GRITA project financing**: EU sustained, with the Strasburg Parliament resolution dated March 1983, the HVDC link between Italy and Greece, the reinforcement of the Community Members electrical networks interconnection being an his hold priority objective. Afterwards EU considered the GRITA project inside the financing programs, supporting the 40% of feasibility studies and realization costs.

1.1 The approach to the problem by Enel-PPC

Notwithstanding the growing application of HVDC links around the world, the utilities consider unusual these systems. Sometime they even constitute a novelty because of their substantial difference from the most widespread AC generation and transmission systems. The acquired experience in the area of DC energy transmission is certainly very useful for an utility but it is not often entirely reusable in possible following applications.

(*) CESI – Via R. Rubattino, 54 – 20134 Milano (Italy)

Fig.1 - Italy-Greece 400kVdc interconnection.

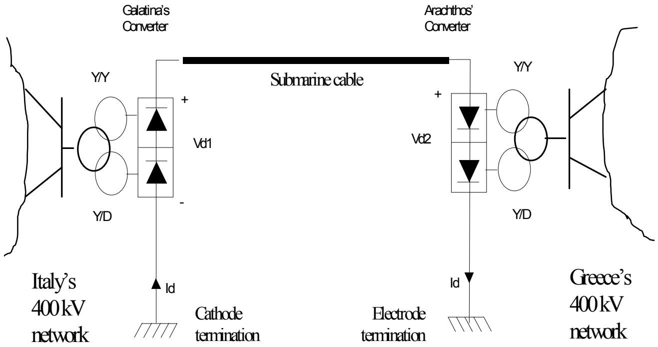

Fig.2 - Synthetic scheme of the GRITA HVDC link.

This occurs for several reasons:

- HVDC systems use technologies based on power and control electronics which have a fast upgrade and involve continuous updating of system design;
- HVDC applications are strongly project oriented, consistently affected by the characteristics of the AC networks they are interconnected and by the functional requirements specified by the utilities;
- HVDC applications are very different and limited (only a few plants each year through the world) making impossible a design standardization.

Therefore detailed review of HVDC system design together with in depth performance testing of system components, control and protection devices and of the overall link are strongly recommended [1]. According with this philosophy, Enel and PPC developed a detailed specification of all the technical aspects of the project and the bidding was based on the review and acceptance of a detailed system design developed by the system manufacturer. Moreover factory and commissioning tests plan must allow a deeply check of each converter station and of the overall link under normal and perturbed conditions. Furthermore the tests should be organized in a way to limit, as far as possible the impact on the AC network. Particular care should be devoted to tune the HVDC control system so as to guarantee that field performances meet specification requirements also for those controls operating under unusual conditions.

2. SYSTEM DESCRIPTION

2.1 General view

The interconnection between the 400kVac Italian and Greek AC networks is an HVDC link which, trough a submarine DC cable, crosses the Otranto channel (see the topographic view of fig.1).

The transmission link is based on a mono-polar scheme with sea return with a rated power and voltage respectively of 500MW and 400kVdc. The system design allows the doubling of the active power transfer moving to a bipolar scheme by installing a second pole.

The HVDC link includes (see the scheme in fig.2):

- two conversion systems - from 400kVac, 50 Hz to 400 kVdc - located in the Galatina and Arachthos stations which include power transformers, smoothing reactor, filters;
- a land DC cable at 400kVdc running on about 43 km between Galatina and Otranto in Italy;
- another short section of land DC cable (less than 1 km) at Aetos in Greece;
- a submarine DC cable of 163 km, between Otranto and Aetos, crossing the north side of Corfù island;
- an over-head DC line along the 110 km between Aetos and Arachthos station in Epiro;
- two submarine electrodes and related ground connections at the Italian and Greek costs.

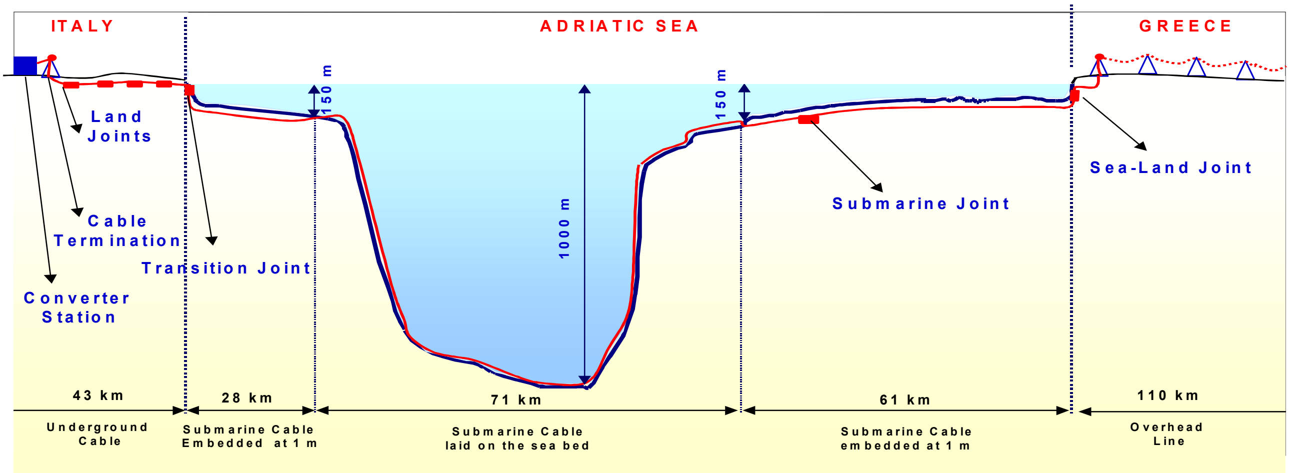

Fig.3 - The schematic bathymetric profile.

2.2 *Cables*

2.2.1 *Submarine cable*

The schematic bathymetric profile is shown in fig.3. The submarine portion is subdivided in three sections: shallow water 28 km long, deep water 71 km long, shallow water again for the remaining 61 km up to the second land-sea joint on the Greek coast at Aetos, facing Corfù island.

The cable conductor is made up of a central copper rod surrounded by four shaped copper segments to give nominal cross sectional area of 1250 mm². For the insulation special high density paper tapes were used and impregnated with viscous compound. Lead alloy sheath "E, containing antimony" was chosen due to its good mechanical characteristics: it avoids penetration of moisture into the insulation. The protective sheath is made of polyethylene, it has been applied immediately on the lead sheath. Its purpose is to act as anticorrosion protection. Polyester tapes and a reinforcement made of galvanized steel tapes (two layers) are applied over it. The armor consists of two layers, counter-helical applied, of galvanized high strength steel flat wires. Fig.4 shows the cross sectional drawing.

2.2.2 *Submarine installation*

The remarkable length of the submarine link has required the installation in two laying campaigns with Pirelli cable-ship Giulio Verne, equipped with a turntable having a capacity of 7000 tons. The utilization of a turntable is mandatory when the cable is provided with a double layer of counter-helical steel flat wires, able to support the cable weight in section having the maximum water depth. This armor configuration requires that the cable be wound (loading) and unwound (laying) from a rotating platform able to avoid any torsional effect.

The great capacity of the turntable has allowed making the entire Italy-Greece connection using only one intermediate field joint, realized at about 60 km from the Greek coast.

The method selected for the cable protection was the cable embedding at 0.6-1 m into the seabed, down to a water depth of 150 m. This method has proved to be effective against external damages, in particular from fishing gears having usually a penetration into the seabed lower than 0.3-0.4 m.

The embedding machine used for such operation is constituted by an ROV, equipped with a high pressure jetting system removing the sand under and around the cable, thus allowing its sinking at the desired depth.

2.2.3 *Land cables*

Different land cables have been used in Italy and in Greece. An oil filled cable was used in Italy, with nominal cross section 1200 mm². For the insulation low viscosity insulating oil was used for impregnation. Lead alloy sheath E was chosen. For the reinforcement and external protective sheath, bronze tapes and medium density polyethylene were adopted. On the Greek side a mass impregnated cable was used, with characteristics similar to the submarine cable, but with a cross section increased to 2000 mm^2 necessary to face the worst thermal conditions. The submarine armor has been substituted by a protective polyethylene jacket.

2.2.4 *Land installation*

The land connection is composed by a high voltage cable, already described, two medium voltage return cables for the marine electrodes, a triple conduct for the telecommunication cables and a pilot cable for the check and surveillance of the line.

All components are installed in the same trench (see the scheme in fig.5). In some sections along the land cable route a new installation technique, called Mechanized Laying, has been used. The basic concept is to dig the trench and to lay the cables in one operation.

This laying method was initially limited to cables having small dimensions, i.e. telecommunication cables and medium voltage power cables and was here applied to big cables for the first time, with a purposely designed system.

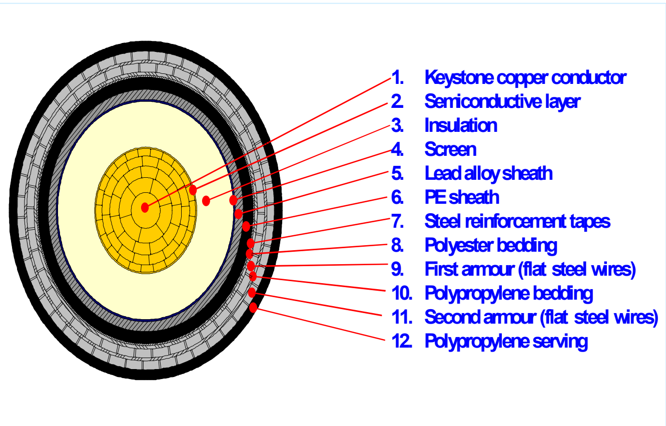

Fig.4 – Submarine cable cross-sectional drawing.

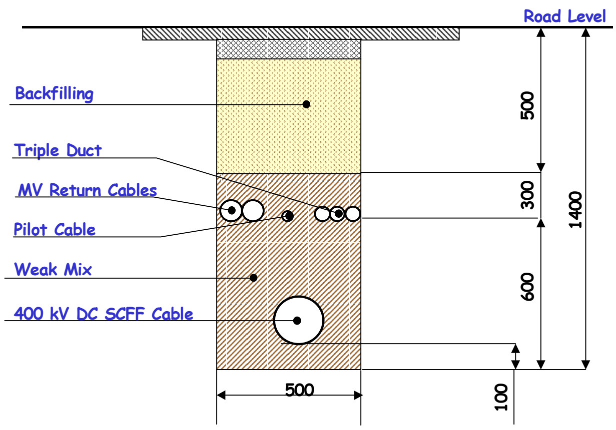

Fig.5 – Land cable installation trench scheme.

2.3 Electrodes

The Italy-Greece mono-polar link re-closes the connection by the sea acting as return cable. This practice, common in submarine HVDC connections, takes advantage of the high conductivity of the sea water, due to a great presence of salts. For the current return through the sea two metallic electrodes have been designed and manufactured. The anode, is located in Greece off the Corfù strait (see fig.6), the cathode, is located in Italy, narrow to Otranto Cape.

Fig.6 – The anode located on the Greek coast.

A small isolated lagoon, separated from the coast by a thin strip of land, has been selected for the anode location. In order to improve the fresh water exchange between sea and lagoon an opening has been realized, by means of three concrete pipes of 1 m diameter. The anode dispersion relies on 39 electrodes titanium bars made, covered by noble metal oxides, a material widely tested for cathode protection with impressed current; it is characterized by a very high corrosion resistance and has a high expected life. A simple bare conductor has been used for the cathode, which is not subject to corrosion. It was installed at about 30 m water depth, slightly raised above the sea bottom in order to allow a better current exchange and an easier inspection.

2.4 Converter Stations

2.4.1 Electromechanical equipment

Besides AC yard breakers and disconnectors, current and voltage transformers and HV bus-bars, the DC converter station is characterized by standard design as concern AC filters, DC filters (at Arachthos only), converter transformers (three single-phase units with a rated size of 200MVA each), air-core smoothing reactors, etc. The converter system includes the 12-pulse thyristor bridge, with three water cooled sections for four valves each. The structure is hang up the roof (see fig.7). The converter system includes also arresters, valve hall grounding switches, DC bus-bar system inside the valve hall for the pole and electrode interconnections and gas-insulated wall bushings.

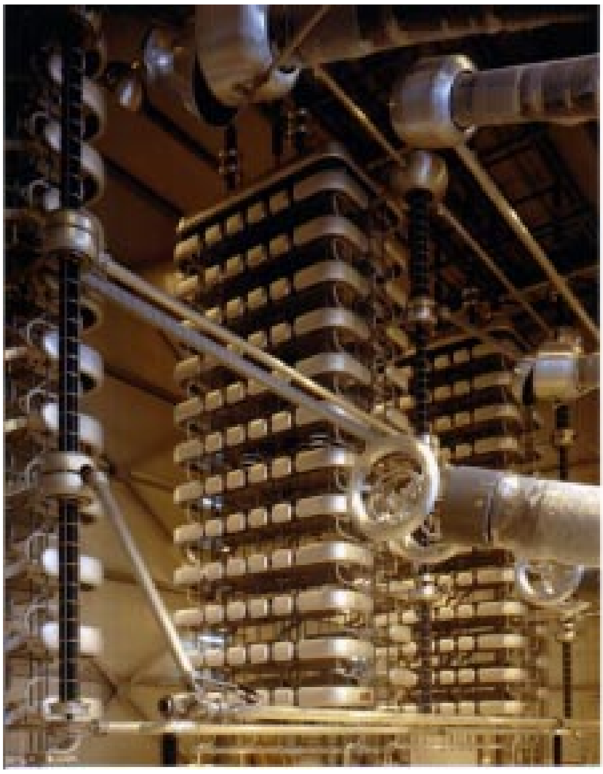

Fig.7 – Thyristor bridge structure.

2.4.2 Control, command and protection system

The system is fully microprocessor based and adopts a high performance distributed architecture. The system configuration is symmetric for both the stations. The system allows the link operation in one of the two admissible control modes: at constant power regulation, in normal operating conditions, or in frequency control, under abnormal network conditions.

The normal operation is in “Automatic Link Mode” (ALM), where the two terminals are automatically coordinated by telecommunication and maneuvered through synthetic commands ordered locally or remotely at the master station. Without tele-communication the ALM allows a reduced set of operational maneuvers.

In “Automatic Terminal Mode” (ATM) each terminal is operated by its own, always through synthetic commands, ordered after a phone coordination by both the operators at the Galatina and Arachthos converter stations. This operating mode is used in case of long telecommunications failures.

The “Manual Mode” (MAN) is only used for maintenance, commissioning and test.

The monitoring and diagnostic system includes specialized features like event reporting, transient recording and harmonics analysis.

The user interface is based on advanced graphical MMI.

Also the protection system, covering AC bus, transformers, filters, converters, pole and electrode lines, is fully microprocessor based and its is physically integrated in the control system.

2.4.3 Main functional characteristics

Besides the nominal performances (at the rated voltage of 400kVdc and the rated current 1250A, the rated power is 500MW) the system has a minimum operation limit (50MW) and can be operated at reduced voltage (at 320KVdc with a reduced current of 1000A, the reduced power is 320MW). At the rated power of 500MW and with an ambient temperature of 40deg the guaranteed conversion losses are about 7MW while the DC line losses are about 14MW.

According to the above defined performances, the link operation is allowed with at least one 400kVac line in service (with a minimum short circuit capacity of 3600MVA in Italy and 2800MVA in Greece). The system performance are automatically reduced in case of one electrode line out of service (the maximum current is reduced to 900A), thyristor over-temperature (the transmitted power is progressively reduced with steps of 5%), ambient over-temperature or spare cooling system unavailability (the current or power order is immediately frozen).

The main operational sequences allow the conventional transitions (pole connect/isolate, converter transformer energize/de-energize, converter valves block/de-block, link start/stop/emergency, power direction selection, operation mode selection, control mode selection, power/current order set, normal/reduced voltage transition) and the following specific features:

- **Slow inversion**: this maneuver reduces the power with a fixed ramp speed (max 999MW/min) up to the technical minimum where the converters are blocked. Then the de-ionization time of 10min is automatically elapsed before de-blocking valves and reaching a new power level with reversed direction. They are allowed up to 1000 times/year with a min time interval of 2 hours.
- **Open Line Test**: DC line voltage energization from one station with the DC pole disconnectors of the other station opened. This maneuver allows to check the DC line insulation for maintenance.
- **Backup Synchronous Control** (BSC) in case of telecommunication fault: once enabled (from each station separately) the activation of BSC is automatic and allows the power or current order change with auto-synchronization of the stations.
- **Restart attempts** after DC line protective action: once enabled (from each station separately) this feature allows the automatic execution of three restart attempts (two at full voltage and one at reduced voltage) before blocking the link.
- **Frequency control** in case of islanding of the grid surrounding the converter station: once enabled (from one station relevant to the islanding of the other station) the activation of frequency control is automatic (based on a logic which considers the frequency deviations values and derivatives). The frequency controller droop and the power regulation band can be fixed by the operator.
- **Fast inversion** in case of islanding of the grid surrounding the converter station: once enabled (from one station relevant to its transition as exporting) the activation of fast inversion is automatic (based on a logic which is triggered under modulation of frequency controller by the transition below the technical minimum). This maneuver reduces the power with a fixed ramp speed (max 999MW/s) up to the technical minimum where the converters are blocked. No de-ionization time is expected before de-blocking valves and reaching a new power level with reversed direction. They are allowed up to 10 times/year with a min time interval of 10 hours.

The following control modes are allowed: in remote ALM with tele-communication power regulation or frequency control, without tele-communication only power regulation (if BSC is enabled); in local ALM: with tele-communication power or current regulation or frequency control, without tele-communication only power or current regulation (if BSC is enabled); in local ATM and MAN asynchronous current control.

As concerns the tap-changer control, on the rectifier side it is devoted to regulate the firing angle, on the inverter side it is conceived for controlling DC voltage.

3. SYSTEM STUDIES AND DESIGN

The relevant aspects of system specification and design are mentioned in the following.

3.1 Main network and system specifications

The main characteristics and requirements specified for the AC networks are the followings:

- The 400 kV nodes to which the converter stations are connected are relatively strong compared to the power of the DC link, in particular the Minimum Short Circuit Ratio is larger than 5 and 7, respectively in Greece and in Italy. Two 400 kV lines are connected to both converter stations, with interconnection to the 150 kV distribution network.
- Both AC networks can supply 140 MVAr and absorb 100 MVAr, while the maximum size of single bank to be switched is 100 MVAr.
- Normal and exceptional operating ranges in terms of voltages and frequency have been considered. In general the normal ranges have been imposed to respect performances while exceptional ranges for rating purposes. Similar criteria have been applied for the negative sequence voltage level and for the pre-existing harmonic voltage levels, considering normal and larger values respectively to meet performances and ratings.

The main characteristics and requirements specified for the system are the nominal power (500 MW, to be guaranteed at the inverter side, pole to neutral), the harmonics on the AC side (normal values have been specified: individual harmonic distortion Dn<1% and 0.7% respectively for odd and even harmonics; total effective harmonic distortion Deff<2%, n=2..50; telephone harmonic form factor THFF<0.9%, n=1..50), the harmonics on the DC side ("equivalent disturbing current" Ieq along the pole and electrode lines must be lower than 2.0 A and 3.0 A respectively for normal and reduced voltage operation, taking account of the pre-existing harmonic values on the AC sides), the transient performances (mainly in case of partial or total loss of AC network). For converter station components type and acceptance tests have been generally specified with reference to IEC Standards. A special "endurance" test was required for the AC filters capacitors taking account of the tendency to increase electric gradient design.

3.2 Marine survey and sea-trial

At the planning stage of the system, it appeared that the Italy-Greece HVDC interconnection would have presented two major difficulties, firstly the installation across the Otranto channel with the record water depth of 1000 m, never previously reached for a power cable and secondly the operational mode with repeated inversions of power direction. The transition joint between the Oil Filled land cable and the Mass Impregnated submarine cable and the huge Porcelain Insulators, suitable for a very high salinity level, were also challenging accessories to be developed.
An important part of the preliminary feasibility study was a detailed marine investigation in order to collect data relevant to characteristics and profile of the seabed and to define the possible risks due to fishing activities and anchoring. On the basis of the acquired data the best route was selected and the protection for the cable was defined. The marine survey was performed in 1991 with the cable-ship Giulio Verne, the same ship used thereupon for the laying activities of the submarine cable. A complete sea-trial, utilizing 3,5 km of cable, was performed in order to check the full suitability of the equipment and procedures to meet all the installation and protection conditions foreseen.
The test was successfully performed in 1995 and was constituted by the following main phases: embedding machine test in shallow water (about 30 m); embedding machine test down to 150 m water depth; test of cable laying, including repair joint, at 1000 m water depth; recovering of the cable and transfer to Arco Felice factory; electrical test at –600 kV DC for 15 min.

3.3 Studies for system design

In addition to the usual system studies, typically carried out in the framework of HVDC applications (main circuit design, reactive power compensation, fundamental frequency over-voltages, insulation coordination, AC and DC transient over-voltages, AC and DC filters design, component rating for AC and DC filters, transient current requirements, circuit breaker requirements, radio interference, audible noise, availability and reliability predictions, losses, control, regulation and protection requirements), the following specific ones were particularly deepened in order to optimize some peculiar features or performances. These system studies were performed by the manufacturer according to the technical specification. The results of these studies were in-depth discussed and reviewed for approval by the customer.

3.3.1 Dynamic performance study

The final control parameter setting was defined based on simulator runs considering performance of the HVDC system with different AC configurations. The control functions relevant for performance during disturbances were tuned both to optimize the power transfer during the faults as well as to obtain a fast recovery to normal operation after fault clearing. The probability of having commutation failures as a consequence of any disturbance is therefore minimized.
Some particular and more critical events were deeply analyzed, such as the case of operation only with the 150 kV network: the outage of one of the two incoming 400 kV overhead lines (for both stations) must not reduce the performances of the HVDC link, while, in this condition, if a further fault (transient or permanent) on the second line appears, the converter station will remain connected only to the weak 150 kV AC network (through auto-transformers 400/150 kV), whose short circuit capacity is comparable to the rated power of the link. In this scenario the feasibility of a safe shutdown of the link was checked, together with the evaluation of the possible restart, depending on the short circuit capacity of the residual grid.
Operation on 150 kV network, even if in principle possible at reduced power (about 85 MW), has been excluded due to the possibility of a critical resonance between AC filter and 150 kV network at 3rd harmonic and also to AC over-voltages arising at AC filter energization (it should be necessary to change auto-transformer ratio in order to reduce bus-bar station AC voltage before connecting AC filter).

3.3.2 Frequency control investigation

The frequency control investigation examined some islanding transients occurring at the Galatina and Arachthos converter sides of Italy-Greece HVDC link. The starting operating point was chosen corresponding to different working conditions of the link, with power flow both from Italy-Galatina to Greece-Arachthos and viceversa. The frequency deviation during the first instants of the islanding transients, as well as the frequency deviation following power modulation in steady-state islanded conditions, were examined. For each islanding separation, the short-circuit capacities of the residual grids were also investigated and a suitable tuning of the frequency controller was determined. The effectiveness of the fast inversion maneuver under frequency controller triggering, was also checked.

3.3.3 Total loss of AC network

The HVDC link has to sustain the stresses caused by large perturbations, such as short circuits on AC and DC side, energization and de-energization of filter banks, transformers and lines. In particular, the system has to be designed also for total loss of AC network.
At this concern specific simulations were performed taking into account different network configurations, i.e. loss of 400 kV ac network alone without connection to the underlying 150 kV network or loss of 400 kV ac network maintaining connection to the 150 kV level.
Simulation results put in evidence that the most critical cases are related to the total loss of AC network (i.e., before the fault, only one of the two 400 kV lines is connected to the station without 150 kV network) when converter station is working as inverter at the maximum power. In this case, the converter still remains active, commutations do not cease, since the resonant circuit between AC filters and converter transformers may support voltage in the station AC bus, thus the pulsed converter continues to inject energy in the importing AC side. This fact involves an increase in the AC voltage up to the intervention of the AC bus arresters. If no protection is foreseen, in order to stop the HVDC link, in less than 100 ms the stresses on the AC arresters overcome their energy capability (less than 5 MJ). With 400 kV and 150 kV network connected to the HVDC link, the time at disposal to stop the link, avoiding the above stresses, is greater with respect to the case of total loss of AC network.
As a result of these studies a specific protection has been developed and tested.

3.3.4 Single and three phase auto-reclosure

Both in Italy and in Greece a single phase fault determines a single phase auto-reclosure. Moreover, in Greece, for multiphase faults, a three phase auto-reclosure is also performed. With the HVDC inverter station connected to only one 400 kV line, a single phase fault on this line with the opening of one phase of the breaker, generates same stresses as during total loss of AC network. In the disconnected phase, voltage does not decrease, but, on the contrary, due to the delta winding of the converter transformer, it is maintained. Energy injected in the opened phase produces over-voltages, that are limited only by the AC bus arrester.
Also in this case, in less than 100 ms, the energy capability of the AC arrester is overtaken. Several detailed simulations showed that fastness of the conceived protection logic is dependent on the operation conditions; in particular, when HVDC link is transmitting high power level, protection is very fast (within 50 ms), limiting AC arresters stresses at about 60% of their energy capability. Moreover, immunity of the protection regarding AC faults or loss of one 400 kV line with the other one connected to the HVDC station, has been tested in simulation.

4. FACTORY SYSTEM TESTS

4.1 Cable factory tests

A peculiar aspect of the Italy-Greece interconnection is the high number of polarity reversals expected during the cable life. This fact has driven to conceive an additional test, not mentioned in the standards: a polarity reversal aging test constituted of 1000 cycles of polarity reversal (with load cycles), being 2 hours the time between two successive cycles. The following tests was performed on the land cable and accessories:

- On all test objects (OF cable, OF joint, OF termination, transition joint, MI cable, MI termination): load cycles ±800 kV, polarity reversal ±600 kV, lightning impulse 960 kV superimposed to DC 400 kV.
- On the outdoor termination: cantilever (on the porcelain insulator) 4000 N for 60 s, wet withstand -630 kV for 10 min, artificial pollution 420 kV SDD = 0.07 mg/cm2.

4.2 Control system tests

In the Italy-Greece HVDC system, most of the control and protection subsystems are micro-processor based. A lot of subsystem software testing has been therefore performed either in substitute hardware or directly in the target system. As foreseen by the quality assurance program of the manufacturer, the factory test plan was subdivided into different phases:

4.2.1 Functional bench tests

Each subsystem functional part was tested in accordance with its test specification. After the successful completion of each functional tests, most of the programs (application codes)? were installed in the target systems and included in the factory testing towards an HVDC simulator.

4.2.2 Factory subsystem tests

During this phase all interfaces between subsystems were tested, in order to completely check all hardware and wiring, including prefabricated connectors between the individual control and protection cubicles, and to confirm the equipment documentation relevance.

4.2.3 Factory system tests

In this test, which is the most extensive part of the control and protection system validation, the cubicles for control, protection and operator communication were interconnected to each other and to the HVDC simulator, which was used in place of the main circuits. The extensive testing in factory was the primary testing of the control and protection system: in fact the system tests performed at site were in some cases a repetition of the tests performed in factory but with the actual main circuits connected to the real AC and DC systems.

The objective was to debug the system and verify correct interaction between different parts, representing maneuvers, measurements and indication circuits in order to close as many control loops as practically possible. A number of test cases were conducted on control and protection functions and related circuit redundancies. The testing showed also the selectivity for different faults as well as the correct behavior during AC system disturbances.
The results of the factory system tests were compared with specified performance criteria, mainly those not repeated during the on-site acceptance testing stage, to avoid the lifetime degradation of the connected main circuit equipment and/or cause a risk of instabilities in the surrounding AC networks.

In the following some examples of dynamic transients checked during factory system test are shown.
Fig.8 refers to a 3-phase solid fault applied at the Italian network with Galatina operating as inverter and importing 200 MW: the DC peak current, due to commutation failures occurring at the inverter side, as well as the proper recovery, achieved through the rapid DC voltage inversion at the rectifier side, are shown.
Fig.9 refers to a pole to ground fault applied on the valve side of reactor at the Galatina inverter station with a power flow of 300 MW: the protective intervention of the DC differential protection (properly selected with respect to the DC line protection) causes a timely block of the converters, with tripping of the AC bus breaker and de-energization of the transformers and valves.

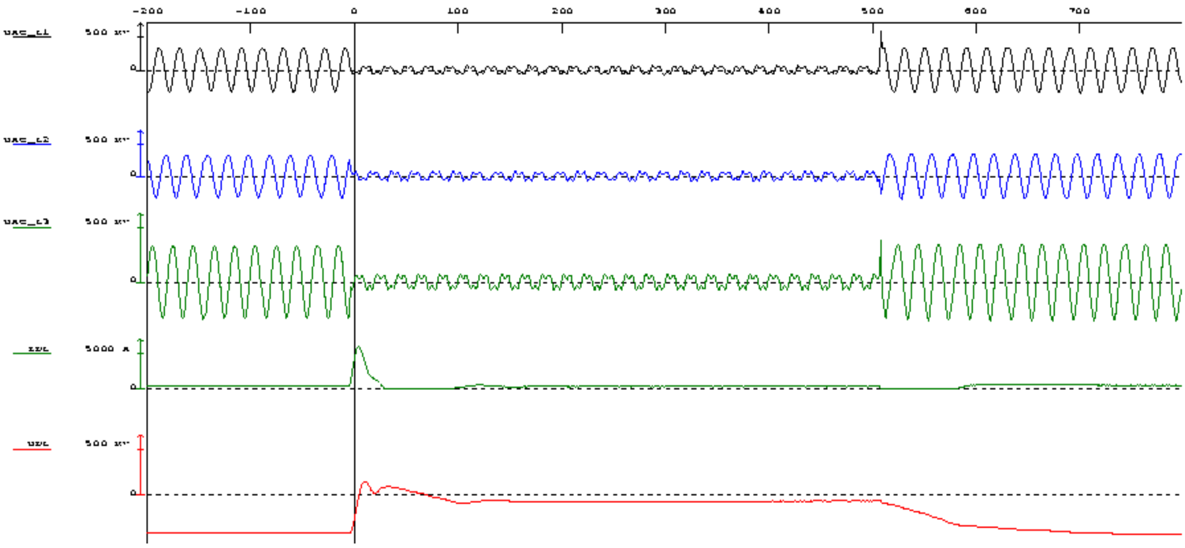

Fig.8 - 3-phase solid fault applied at the Italian network with Galatina operating as inverter.

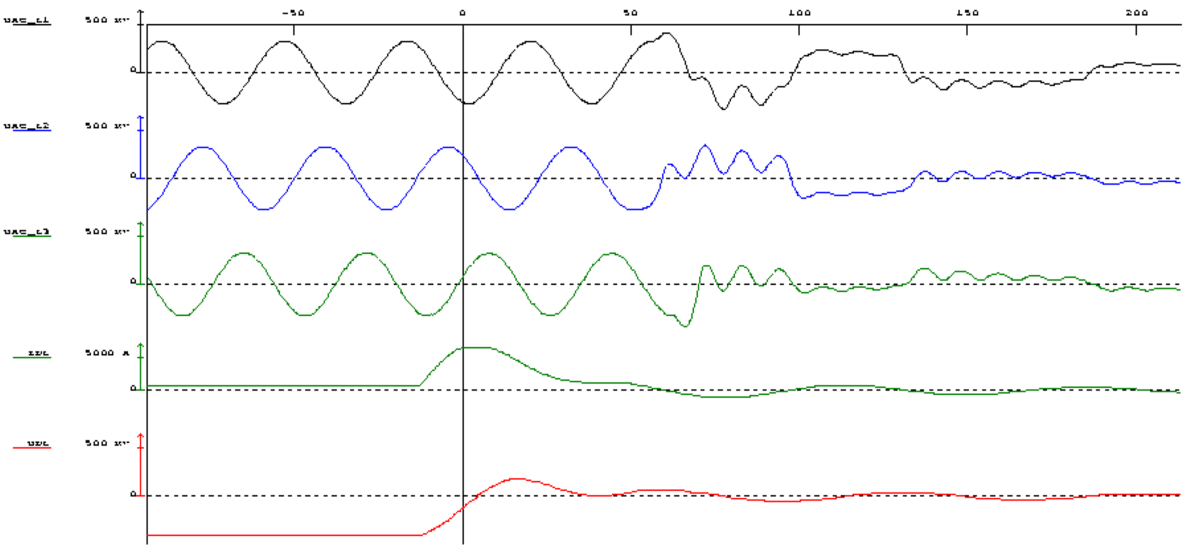

Fig.9 - Pole to ground fault applied on the valve side of reactor at the Galatina converter station.

5. SITE SYSTEM TESTS

5.1 Cable site tests

At the end of installation of submarine cable and completion of all the land sections the whole system has been successfully subjected to an HVDC integrity test at the voltage of 500 kV for 15 minutes.

5.2 Commissioning tests

The testing on the site included full scale tests of all equipment, starting from the high voltage energization, through complete transmission tests, here included acceptance test of guaranteed performance. A major portion of the system tests involved operating the HVDC transmission during normal conditions with the automatic controls activated: several functions were partly or fully tested without affecting power transfer. As foreseen by the quality assurance program of the manufacturer, the site test plan was subdivided into:

5.2.1 Subsystem tests on site

The purpose was the detailed on-site subsystems tests on the interconnected equipment to check the correct pre-conditions to start energization/operation tests.

5.2.2 High voltage energization tests

During the tests the involved parts were kept energized for several hours, checking corona or abnormal noise by visual inspection of equipment and reading surge arresters counters before and after the energization. The energization of converter transformers, thyristor valves and DC yard was made first with blocked valves (AC-side) and later with valves de-blocked (DC-side). This test enables the converter to continuously control the DC voltage following a step-by-step procedure.

5.2.3 Terminal /transmission tests on site

Transmission tests was the final tests where everything works together: controls, main circuit equipment, operators and dispatchers, who had a responsibility in planning power levels and system conditions during the transmission tests. The system tests were divided in two levels: terminal tests with only one HVDC station involved (affecting one station/AC system mostly under high voltage conditions, without coordination between different stations/AC systems) and transmission tests (with power transfer between AC systems).

The tests performed covered current control (check of step response and firing symmetry), tap changer control (checking of firing and extinction angles within their limits), power control (checking that power ramping is controlled in a normal way, verification of power modulation and slow and fast inversion procedures), sequences (checking that the breakers, disconnectors and grounding switches operate safety according to the automatic sequences and with the operators instructions), load and overload (checking of the cooling equipment, primarily the converter valves and converter transformers), measurements (transmissible power, AC, DC and RI harmonics, audible noise).

Some of the system tests were devised as acceptance tests to demonstrate compliance with performance requirements. In the following some examples of dynamic transients during site system test are shown.

Fig.10 refers to dynamic response to current order steps of different amplitudes: the plotted variables (current, voltage, firing and extinction angles) exhibit a stable and fast behavior after the fine tuning of control parameters.

Fig.11 refers to a transient following AC remote fault at the Greek side operating as rectifier: also in this case it is evident the sudden DC current reduction due to the DC voltage drop and the following current recovery when the fault in the network is removed.

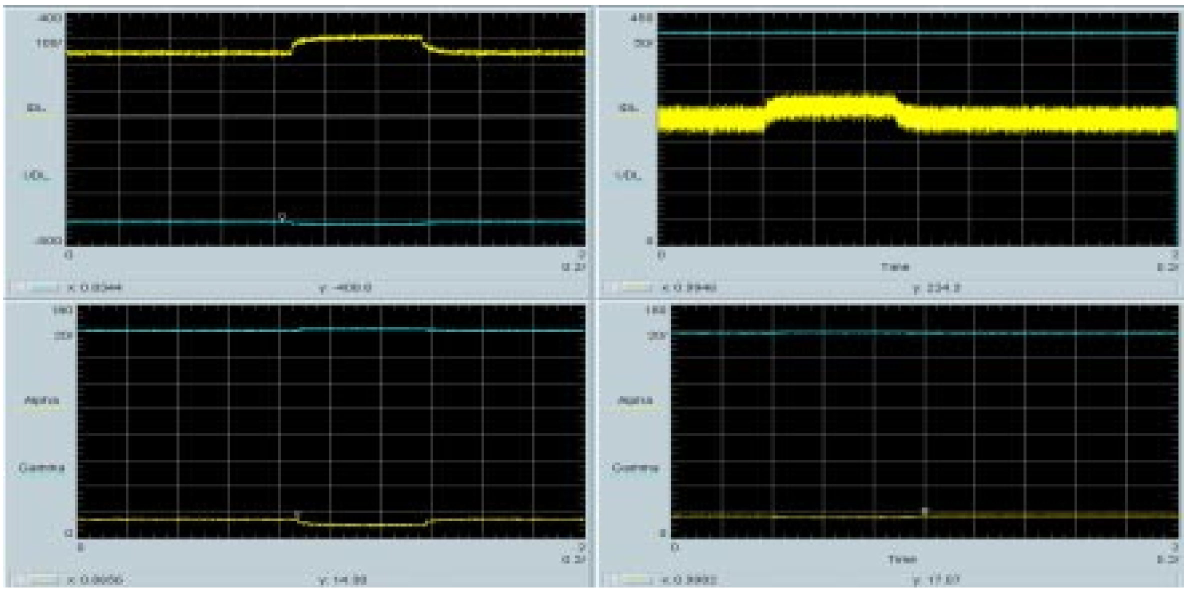

Fig.10 - Dynamic response to current steps of different amplitudes.

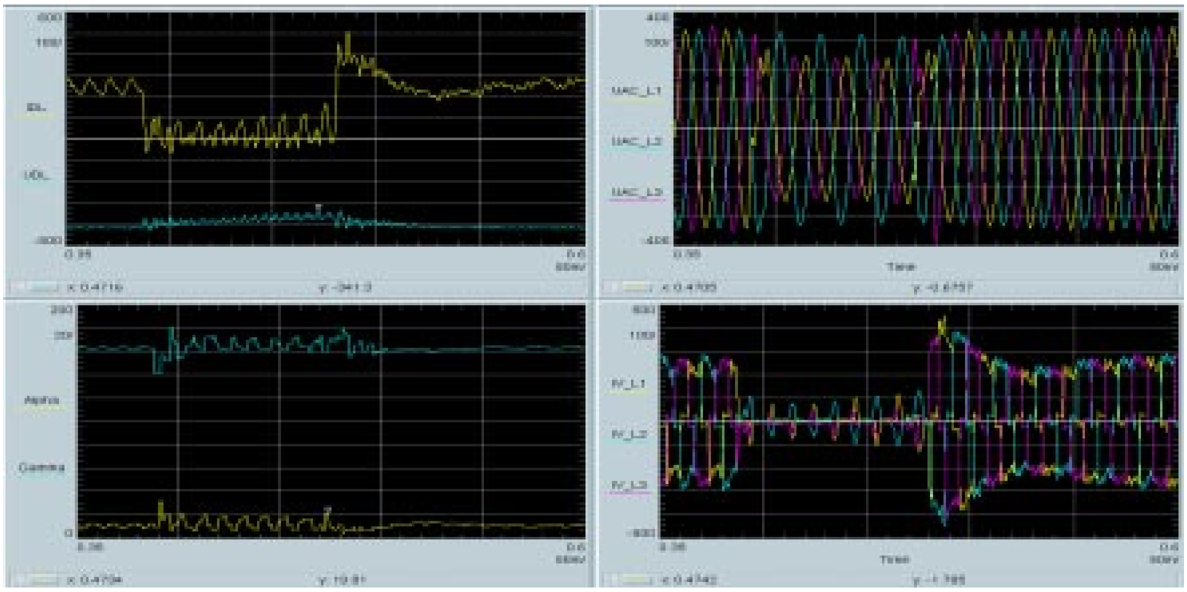

Fig.11 - Transient following AC remote fault at the Greek side.

6. CONCLUSIONS

The Italy-Greece HVDC project reached, in agreement with the dead-line imposed by the EU, which contributed to its financing, all the initial planned objectives, one of the most important being the reinforcement of the links among EU Countries. The system trial operation started from January 2002 and some operation results and checks of the waited link benefits will be available at the time of the Conference.
The system study and design experience have significantly contributed to achieve the specified performances in term of functionality, quality of the environmental impact, robustness of the system components, reliability of the link. The factory and field tests have moreover demonstrated the consistency of the produced study and design effort by the manufactures with a significant contribution by the utilities. In fact during the system design review and testing phases, the most suitable technical choices/upgrade/tuning were recognized, discussed and jointly approved by the manufacturers and utilities, coherently with the expected performances and operation security.
Some peculiar characteristics of the GRITA link have to be considered as relevant improvements with respect to the past realizations:

- the frequency regulation of the islanded AC network surrounding one pole, linked with the automatic power fast reversal maneuver,
- the algorithm which automatically and timely recognizes the islanding state of the local AC grid,
- the current synchronous back up which allows a reduced performances ALM operation from remote, notwithstanding the loss of telecommunication between the two terminals;
- the sure and fast recognition of total loss of AC network through a new protection.

The GRITA link also represents a very important stage in the development of the submarine cables systems, particularly in direct current, for various aspects:

- The maximum water depth of 1000 m, never previously reached for a power cable;
- The voltage and the power, among the highest realized to date;
- The number of test load cycles with polarity reversal (1000), a record to date;
- The length the Italian land cable (43 km), one of the major worldwide for a power cable;
- The characteristics of the laying on land, mechanized with particular contrivances.

On the whole, a work destined to be a milestone in the development of the submarine technology.

REFERENCES

[1] V. Arcidiacono, S. Corsi, C. Pincella, E. Gasparini, A. Piffer, G. Toffolo, P. Ricci, S. Vascellari, G. Zafferani, “System Commissioning Tests for the SACOI–2 HVDC Three-terminal Link”, CIGRE CONFERENCE – Paris, August 1992 – Session Group 14.

[2] V. Arcidiacono, A. Giorgi, L. Pandini, G. Pazienza, R. Rendina, “Compatibilità 2000 – Session elettromagnetica nei collegamenti in corrente continua ad alta tensione Sardegna-Corsica-Continente Italiano (SA.CO.IO e Italia-Grecia)” Study Day AEI-Firenze, Nov. 26 ,1999 .

[3] E. A. Leonidaki, N. D. Hatziargyriou, B. C. Papadias, G. J. Georgantzis, “Investigation of FACTS applications in the Hellenic transmission system considering power flow variations including Greece-Italy HVDC link”, CIGRE CONFERENCE – Paris, August
Group 14.