Emergency-stability controls through HVDC links

S. Corsi, *Member, IEEE*, A. Danelli and M. Pozzi

Abstract — **The paper deals with some power modulation controls achievable by using the High Voltage Direct Current (HVDC) interconnections between different grids or sub-networks. HVDC links can be in fact effectively used for damping electromechanical oscillations, stabilizing power swings, reducing the life-fatigue effects of Sub-Synchronous Resonance (SSR), etc. The development of Voltage Source Converter (VSC) technology (used for instance in HVDC Light interconnections) can improve also the network voltage compensation and the transmission grid load-ability, reducing the risks of voltage instability and collapse.**

The paper mainly focuses on the power modulation strategies designed for two Italian HVDC links, the Sardinia-Corsica-Italy link (SACOI), with more than ten years of commercial operation after refurbishment by ENEL and EDF, and the Italy-Greece link (GRITA), more recently put in service by ENEL and PPC. These mono-polar links with sea return (rated voltage 300 kV and 400 kV respectively, rated current 1500 A and 1250 A respectively, rated power 300 MW and 500 MW respectively) are based on conventional grid commuted double thyristor bridges. The permanent or transient critical conditions of network islanding are faced by high speed and low droop frequency regulators, characterized by flexible and effective control operations.

Index Terms — **Power modulation, frequency control, HVDC link, FACTS controller, electromechanical stability, transient stability, voltage stability, sub-synchronous resonance.**

I. Introduction

THE meshing level between transmission networks has become in the recent years more and more tight, due to the general trend of the utilities and system operators to exploit the networks as close as possible to their maximum transmission capacity and to the liberalization of the electrical industry, which is a well assessed or rapidly on-going process in many countries. In particular the application of High Voltage Direct Current (HVDC) links [1, 2] and compensated AC lines is becoming a frequent transmission design choice, especially in case of very long interconnections, often combined with the adoption of Flexible AC Transmission Systems (FACTS).

In this growing interconnection scenario and in presence of high levels of power exchanges, some network operation problems may occur: increased active and reactive power losses, higher risks of voltage instability or collapse, stronger requirements for the load demands following and higher criticism associated with possible grid contingencies, which typically results the most crucial and important.

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At this concern the simultaneous presence of AC and DC interconnections may create unexpected and additional contingencies, with respect to the AC line faults or trips, due for instance to the DC line faults or commutation failures at the inverter side, with following HVDC link temporary stops.

In all the above depicted scenarios, power modulation controls through HVDC links is a well-accepted technique to enhance AC systems performance. For a long time, such a technique has been used essentially to increase the power transfer capability of an hybrid AC/DC power system and in particular to provide stability benefits to the AC system. Today the practical demands of power systems operation require the HVDC controls to be more able to regulate power flows, under a diversity of operating conditions. At the same time HVDC technology (conventional or light) allows these systems to actively participate in the active/reactive power rescheduling.

HVDC power modulation controls, due to their particular interactions with the AC system and their freedom degrees in power and voltage regulation, could be capable of responding to any deviation from the normal operating conditions in the AC/DC systems: to this aim Voltage Source Converter (VSC) is proving itself to be a very promising technology. Very often power modulation is used to control the frequency of small networks, drawing power from a larger one, to damp power exchange oscillation between interconnected systems, to damp sub-synchronous resonance, to improve the AC system stability and for active and reactive co-ordination: these fast control functions could be on-line or they could act following particular events. For example the frequency control could act continuously, as designed for the Sardinia-Corsica-Italy HVDC link [3], or only following a network separation due to a cascade line tripping driving part of a network to be islanded, as designed for the Italy-Greece HVDC link [4]. The controller could then be always active or triggered by digital status signals or by appropriate thresholds on analogue measurements, such as frequency values or its derivatives.

Also power systems emergency conditions can be very effectively faced by using of HVDC system controls. Transient instabilities for instance are among the most difficult to control, because they require a short reaction time to prevent their spreading. Major incidents, such as the outage of a key power plant or a key substation, rarely occur but can cause, at one or both terminal areas, large load/generation unbalance, posing a threat of transient instability and cascading outages. In an hybrid AC/DC power system, emergency power actions from the HVDC connection result very important, because appropriate fast changes in DC power will reduce the stress on the AC system and the magnitude of the first transient swing.

II. HVDC LINK SPECIAL DYNAMIC CONTROLS

HVDC links are typically operated according to their basic regulation modes, like individual phase rather than equidistant firing control, current control rather than voltage control mode, rectifier injection rather than inverter extinction angle control, power flow control, etc. Some HVDC links are also provided with special dynamic controls, capable of responding to any deviation from the normal operating condition in the AC or DC systems, in such a way to not remain passive to special needs of the interconnected AC systems.

Sometimes these special dynamic controls are exclusively adopted for facing unwanted dynamic interactions between the AC and DC systems, which may manifest themselves in a variety of voltage, harmonic and power instabilities, essentially related to the strengths of the AC and DC systems expressed by the Short Circuit Capacity (SCC). Alternatively such AC/DC interactions can be usefully exploited by using of the fast converters adaptability to achieve an overall more stable operation of the power system under control.

More generally a considerable flexibility degree exists in respect to the levels of power that can be interchanged between AC systems interconnected through HVDC links. This property, already fully exploited in practical applications, is used to provide various types of DC power control, according to the operational needs briefly described below.

A. Network frequency control

The frequency of a small network interconnected to a larger one by an HVDC transmission link can be quickly controlled by means of an additional frequency feedback loop, typically acting on the DC link controls, such that the small network draws the required power change from the larger one.

An example of frequency control is represented by the SACOI link [3] where, at the time of the original design, both the Sardinian and Corsican networks had the power rating and droop of the DC line comparable with or greater than the rating of the running generators in the AC system to which the line was connected: then the line terminal could share in the frequency regulation or even perform it unaided. Conversely, the GRITA link [4] interconnecting the southern Italian and western Greek networks uses a combination of control modes, such that the control signal applied to the current controller is normally power flow, and it does so as long as the frequency remains within predetermined limits. Outside these limits, frequency control takes over to assist the islanded network in emergency; in these operating conditions, if the minimum transmission power is approached, the frequency controller automatically starts a coordinated fast inversion maneuver.

B. Small signal stabilization

In tightly connected systems dynamic instability is rare and electromechanical swings are usually well damped for their characteristic frequencies; however, in case of long and relatively weak interconnections between large systems, low frequency swing modes may result. An Italian example of these modes has appeared in the framework of the planning studies related to the new AC line interconnection between Sardinia and Corsica, in parallel to the existing DC link; another example in Italy could be represented by the AC cable interconnection between Sicily and Italy. In a worst case scenario, the response of the power system controls to the synchronizing swings associated with these low-frequency modes can produce sufficient negative damping to cancel the usual positive damping of the power system, so causing the occurrence of oscillations with increasing amplitudes. For damping these oscillations a control system to modulate the HVDC link power flow could be developed: a typical solution [5] may be based on the small signal modulation of the DC power, in proportion to the frequency difference across the AC systems or to the power flow between themselves.

C. Large signal stabilization

While the small signal modulation above described is suitable to maintain the state of equilibrium, it results often inadequate for the damping of very large disturbances: in this case large signal stability control is thus needed to regain the state following large disturbances, forcing for instance predefined higher steps in current order or angle set-point.

On this concern, with the increased power ratings of recent HVDC transmission schemes and with the introduction of VSC technology it is becoming more frequent to assess the effect of alternative converter control strategies on the transient stability levels of the interconnected AC systems. The thyristor valves used in HVDC transmission are in fact rated to withstand considerable overloads, without adverse effects to avoid unnecessary protective action, and this capability provides the basis for the first peak transient stability improvement. Each particular emergency strategy, i.e. current increase or decrease, temporary power reversal, etc. will use special purpose controllers, responding to power-frequency and even absolute phase changes and giving the possibility to provide DC power burst to reduce first swing stability peaks.

Furthermore in case of AC systems interconnection through a tie line, a disturbance occurring on one system normally causes the trip of the line to prevent the disturbance itself affecting the other system, but at the same time the system in difficulty loses an essential in-feed. An HVDC link instead, even if equipped only with its basic controls, is capable to shield one system from disturbances on the other. In addition, although the specified power flow can continue, it is possible to vary the DC power setting to help the system in difficulty to the extent which the healthy system can allow, without putting itself in difficulty, and subject to the rating of the link. An appropriate control is therefore capable to propagate a disturbance originated in one system with a predetermined attenuation to the other system, without requiring any particular overload capability as to get through the first swing, exclusively by timely DC power set-point reductions [6].

D. Damping of sub-synchronous resonance

The interaction between torsional oscillation modes of turbine-generators and system oscillation modes of the electric power transmission systems is dominated, with a pure AC transmission system, by a synchronizing component with a relatively small negative damping, due to the resistance of the AC transmission line. In addition the damping windings and the mechanical effects resulting from steam flow, friction, etc. contribute to provide a relatively large positive damping to the torsional modes of vibration of the turbine-generator shafts, which are therefore normally stable when connected to an AC transmission system. In presence of an HVDC system, its equivalent apparent loads changes slightly depending on the absence of control (which contributes with a positive damping characteristic) or more commonly in practice on the presence of the current control loop (which changes the impact of the DC system as one of negative damping). The potential destabilization of torsional oscillations due to HVDC systems is similar to that caused by series compensated AC transmission lines and is commonly referred to as Sub-Synchronous Resonance (SSR). The dynamic interaction with DC systems can be solved relatively simply by providing DC power modulation control to cancel the negative damping impact of the basic constant power control loop [7].

E. Voltage regulation and compensation

A control of the reactive power supply, to match the reactive power demand depending on the active and reactive power characteristics of the converter, is essential to minimize voltage variations at the AC terminal voltages of the converter stations. In particular, the reactive power demand may vary widely during transients and the duration of such variations depends to a large extent on the characteristics of the DC link control system. During HVDC link disturbances a dynamic voltage regulation is often adopted and its requirements depend on the nature and location of disturbances. A slow or fast control of the reactive power consumption is therefore achievable with the result of a considerable over-voltage limitation following the disturbance [8]. An additional compensation equipment is also often used to support the dynamic voltage regulation, to help in the recovery of the AC system from faults, and to reduce the disturbances resulting from DC load variation or from the switching of filter banks. The evolution of VSC technology will allow, in the typical HVDC Light configuration, the exploitation of the high side voltage control and reactive power compensation features, with characteristics similar to those of STATCOM controllers.

It has to be observed in conclusion that the degree of DC power modulation which can be achieved by an HVDC link is restricted by terminal reactive power constraints. With only current or power modulation, under a frequency regulation or a stabilizing control, an increase in active power transfer will be also accompanied by a larger increase reactive power requirements and this effect is particularly noticeable during severe system disturbances. The reactive power variations can cause current control mode transitions between the rectifier and the inverter terminals, and subsequent DC current changes equal to the DC system margin current. A proper coordination between the active and reactive power modulation [9] can be achieved by DC system voltage modulation. In fact an increase in DC voltage will increase for instance the DC power transfer, as well as the power factor at both terminals, and hence the reactive consumption as a percentage of active power.

III. The Frequency Control of the GRITA Link

The new Italy-Greece HVDC link, whose commissioning has been finished during 2001, has been realized by ENEL and PPC, with the engineering support of CESI and manufacturers ABB and PIRELLI. 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 both from Galatina (Italy) to Arachthos (Greece) and vice-versa. This HVDC link is based on a conventional grid commuted twelve pulse thyristor bridge and is already conceived for a possible 1000 MW bipolar extension.

The GRITA link 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 control, pole power regulation and power-frequency regulation, inter-station telecommunication, station control and monitoring).

The GRITA link regulator allows two alternative functions: constant power regulation (normal regulation working state) and power-frequency regulation (exceptional regulating state during network emergency conditions). For both the working modes the power transfer regulation of the rectifier terminal is operating, that is the output of the power regulation constitutes the current set-point of the rectifier terminal. The current order is obtained by dividing the total power order by the direct voltage response and, once limited from an overload limit, is fed to the synchronization unit in which the current set-point is synchronized between the two stations.

The set-point of the power regulator is given by a "base power" calibrator output to which is added, in case of power-frequency regulation, the output ΔP of a network Frequency Control (FC), whose range is limited by operator setting of the power band allowed. The FC is active in one station at the time and the power contribution ΔP corresponds to frequency deviation from nominal value in the corresponding AC network. The FC provided in both stations is of a PID type (proportional, integrating, derivative) with a low frequency correction of the integral path (with finite and not null droop).

The power-frequency regulation function faces the islanded network working conditions of one of the two terminals. This control function, when manually enabled by the operator, is automatically activated on the base of frequency deviation measurement (difference compared to the nominal value), according to the logic described in the following.

It is important to underline that when an exporting network becomes islanded, so activating the power-frequency regulation, if a reduction of the power transfer to the technical minimum occurs, in this case the control system operates a fast inversion of the power flux. Therefore the considered network becomes importing under power-frequency regulation, with the base power set-point at the technical minimum.

The fast inversion part during islanded operation will be covered by the Delta Power Control (DPC) function. In the case of islanded operation, when the FC reaches the HVDC link technical minimum, the DPC, if manually enabled by the operator, will automatically initiate a fast adaptation of the power to a predefined level and direction (the technical minimum with the opposite sign). The DPC has to be manually enabled by the operator (the max/min limits are adjustable). DPC has to be an automatic activated function (in a coordinated way with the FC) and the function can be enabled or disabled from both the stations. The activation criteria to both the FC has been checked and fine-tuned using electromagnetic investigation tools or stability programs. The fastest inversion of the power direction of the DPC function is 999 MW/sec. Both ramp rate and power level can be manually adjusted by the operator. It is evident that after one fast power reversal, the same feature has to be automatically disabled for the time requested for avoiding excessive cable stresses.

A. FC islanding detection logic

The AC network islanding detection logic has been based on the over-exceeding of predefined values and/or derivatives thresholds of the network frequency following grid islanding. A preliminary setting for the frequency value and derivative thresholds has been achieved through a simulation based analysis, which evaluated different realistic islanding scenario, associated with the corresponding reduced equivalent inertia:

$$FC\_on = (abs(\Delta f)\ .gt.\ (0.25\text{-}0.5\ Hz))\ .and.\ (abs(df/dt)\ .gt.\ (0.5\text{-}1.0\ Hz/s)) \quad (1a)$$

rather than:

$$FC\_on = (abs(\Delta f)\ .gt.\ (0.25\text{-}0.5\ Hz))\ .or.\ (abs(df/dt)\ .gt.\ (0.5\text{-}1.0\ Hz/s)) \quad (1b)$$

The choice (1a) is more prudential, because causes the FC intervention when both the grid frequency values and derivatives exceed predefined thresholds (it means that FC is not activated in presence of a large island, with high inertia and low frequency derivatives). It has to be pointed out that in this case a time elapsing logic (time windowing interval started by the derivative exceeding) has been designed, for relating the min/max of the derivatives and the min/max of the values: this because the derivatives exceeding typically anticipate the values exceeding of a certain amount of time (about 1 sec). The choice (1b) is more timely, because causes the FC intervention when either the grid frequency values or derivatives exceed predefined thresholds (it means that FC is activated also in presence of a large island, with high inertia and low frequency derivatives). It has to be pointed out that in this case a suitable filtering logic has been designed, mainly on the derivative calculation and depending on the actual solution proposed by the manufacturer, for avoiding not necessary frequency control commutations, being typically the derivative exceeding more probable and very anticipate (about 100 ms). The more suitable design solution has been defined after the detailed investigation, in the transient stability timeframe and during the commissioning activities in the field.

B. FC islanding power modulation

The islanding power modulation law, applied to the identified transfer functions from power modulation to islanded network frequency, may be based on the linear first order lead-lag transfer function:

$$G(s) = 1/Bp\ (1+pT1)/(1+pT2)\ *Pn/Fn \quad (2)$$

with the time constants respectively placed at $T1$ = 3.3 s and $T2$ = 10.0 s and the droop gain Bp expressed in p.u./p.u. The frequency nominal value Fn is 50 Hz while the power control value Pn may be changed depending on the islanded grid size. A preliminary setting for the droop gain Bp has been 5%, while the power control value Pn has been ranged between 500MW (for the small islands scenario realistic for the western Greek network) up to 5000MW (for the high islands situation typical of the southern Italian grid); in other terms the droop gain Bp may be ranged between 0.5% (for the high and quite interconnected Italian grid islands) up to 5% (for the small and critically feasible Greek islands), if the power control value Pn is considered fixed at the rated power of 500 MW.

C. DPC fast inversion logic

As regards the fast power reversal activation logic, it has been investigated the necessity to use not only the actual power level (compared with the technical minimum) but also its derivative (compared with suitable thresholds): this for avoiding not necessary power reversal and related cable stresses. Also in this case two solutions could be adopted:

$$DPC\_on = (abs(Pref)\ .lt.\ (50.0\ MW))\ .and.\ (abs(dPref/dt)\ .gt.\ (500.0MW/s)) \quad (3a)$$

rather than:

$$DPC\_on = (abs(Pref)\ .lt.\ (50.0\ MW))\ .or.\ (abs(dPref/dt)\ .gt.\ (500.0MW/s)) \quad (3b)$$

D. FC and DPC simulation results

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), a frequency control specific study was particularly deepened in order to optimize the related peculiar features or performances.

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 vice-versa. 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. Fig. 1 and 2 put in evidence two examples of dynamic behaviors obtained through EMTDC simulation in case of islanding transients occurring at the Italian side (Galatina terminal operated as rectifier) of the GRITA link. In Fig.1 the FC power modulation causes a rectifier power reduction, due to the under-frequency transient (power deficit in the separated grid), within the allowed band (450MW) and above the technical minimum (50MW). In Fig.2 instead the rectifier power reduction under FC power modulation is stronger, due to lower under-frequency transient (higher power deficit in the separated grid), and causes the activation of DPC. Once completed the fast inversion the FC can continue the power modulation up to the new required rectifier power.

IV. THE FREQUENCY CONTROL OF THE SACOI LINK

The Sardinia-Corsica-Italy HVDC link consists in a mono-polar link with sea return, with a rated voltage of 200 kV, a rated current of 1500 A and a rated power of 300 MW, which can flow both from Suvereto (Italy) to Codrongainus (Sardinia) and vice-versa. This HVDC link is based on a conventional grid commuted twelve pulse thyristor bridge and has a third terminal tap station (50MW) at Lucciana (Corsica).

The SACOI frequency regulation loop was designed to face rapidly (within 10s) sudden variations of the load or of the generation in Sardinia, with a power participation share of about 2/3 of the disturbance. In fig. 3 the power imported in Sardinia by SACOI and the frequency of the Sardinian network following tripping of a generation unit of about 80 MW are illustrated. The results demonstrate behavior substantially in agreement with design data.

The behavior of the system was checked for the slow reversal power flow command between the two main terminals and also the response to the rapid reversal of the main terminals (following an operator command or through the intervention of frequency protection of the Sardinian network) and of the Corsican terminal alone. Fig. 4 shows the result of the fast reversal test of the main link in tri-terminal operation: reversal on the main link occurs in about 300-400 ms while the Corsican terminal recovery is completed in about 1s.

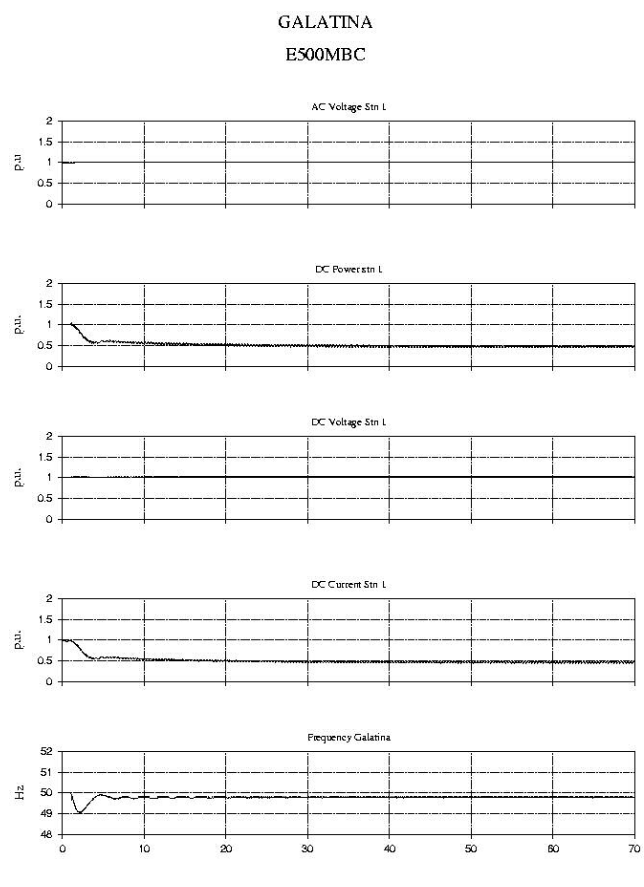

Fig. 1. Simulation of islanding transient occurring at the Italian side (Galatina terminal) of the GRITA link with activation of FC (Δpmax=450MW).

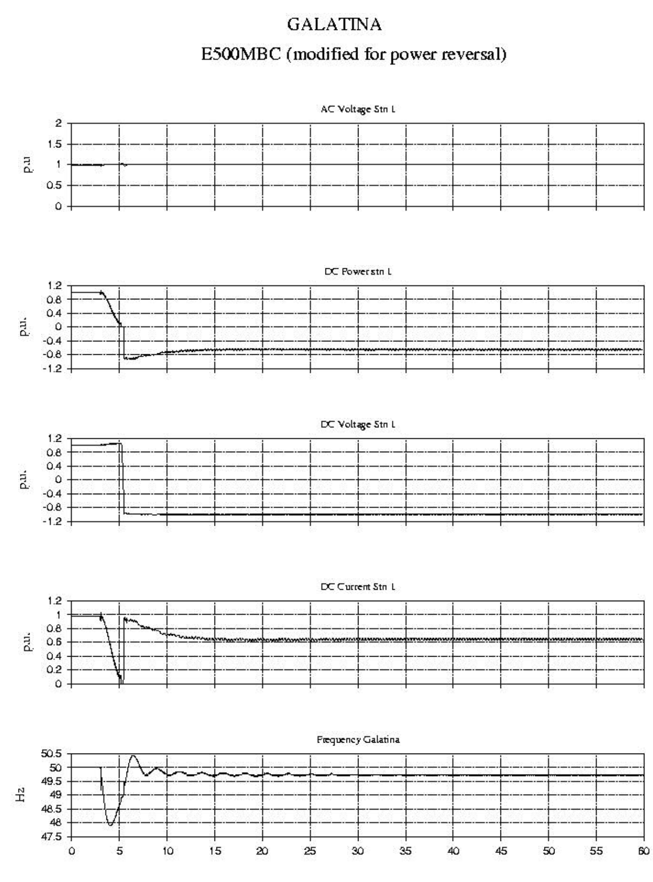

Fig. 2. Simulation of islanding transient occurring at the Italian side (Galatina terminal) of the GRITA link with activation of FC+DPC (Δpmax=450MW).

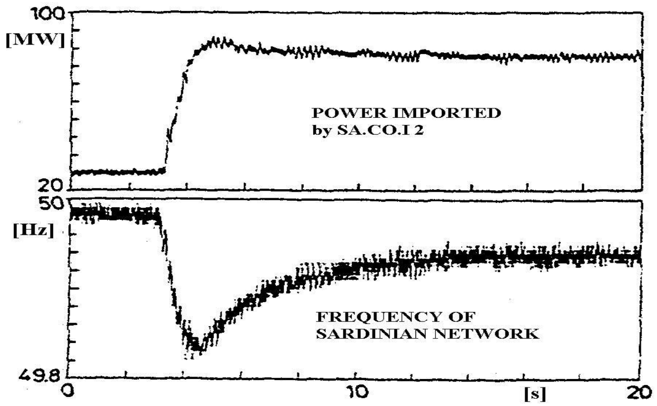

Fig. 3. Commissioning FC test following unit trip occurring at the Sardinian side (Codrongianus terminal) of the SACOI link.

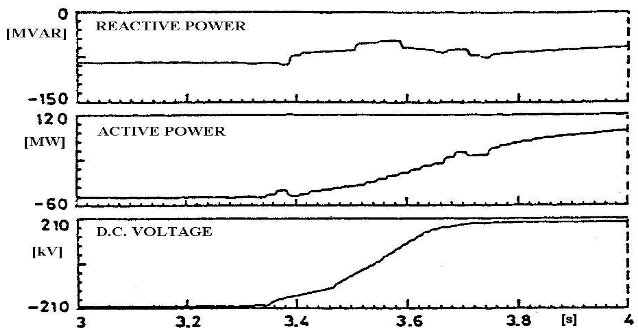

Fig. 4. Commissioning DPC test following manual command operated at the Sardinian side (Codrongianus terminal) of the SACOI link.

V. Conclusions

The paper has discussed some power modulation controls achievable using the HVDC interconnections, in the framework of frequency control, damping electromechanical oscillations, stabilizing power swings, reducing the life-fatigue effects of SSR, etc. In particular the paper has focused on the power modulation strategies designed for two Italian HVDC links, the SACOI and the GRITA links.

For these links, high speed and low droop frequency regulators, characterized by flexible and effective control operations, have been designed for the critical conditions of network islanding and for a type of operation permanent or transient respectively. The control requirements concerning such Italian links, in terms of main control and regulation functionality, control and regulation dynamic performance, telecommunication between converters, have been also discussed in detail. The frequency control of the GRITA link has been in-depth explained, describing the specifically designed FC islanding detection logic and power modulation law, as well as the DPC fast inversion logic. The frequency control of the SACOI link has been more shortly introduced.

Some GRITA simulation tests and SACOI commissioning results have been also shown, proving the high control flexibility and regulation performance achievable by using of HVDC power modulation, in particular for facing unexpected contingencies, like lines outages and following grid islanding, with large load/generation unbalance and high risk of transient instability and cascading trips phenomena.

VI. References

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VII. Biographies

Sandro Corsi received his Doctor degree in Electronics (Automatic Systems), from the Polytechnic of Milan (Italy) in 1973, where was assistant professor at Electrical and Electronic Department. In 1975 he joined to Automatica Research Center of ENEL. The main interests were: power system voltage control, generator control, power electronics devices, advanced controls, advanced control technology for power systems, power system automation. Research manager at Enel S.p.A Ricerca from 1997, as responsible of "Power System Control & Regulation" office. After ENEL reorganization, research manager at CESI as responsible of “Network & Plant Automation" office from 1999 and of "Electronics & Communications" office at the Automation Business Unit from 2000. From 2001 at the CESI R&D Central Depart. Member of CIGRE, IEEE-PES and CEI WGs and SCs. Member of PSCC02-TPC and IREP Board of Directors. Author of more than 60 technical papers on the main Conferences publications and Reviews on power system control.

Aldo Danelli received his Doctor degree in Electronics (Mathematics), from the Polytechnic of Milan (Italy) in 1998. In 1989 he joined to the Automatica Research Center of ENEL, where he worked as Researcher in the control system and voltage regulation department. In this period his main interest was in the field generator regulation, wind and photo-voltaic unit control, farm design and field tests. Since 2000 he is been working in CESI within the T&D Networks Business Units and Automatic Business Units, in the framework of grid supervision and control.

Massimo Pozzi received his Doctor degree in Electronics (Automatic Systems), from the Polytechnic of Milan (Italy) in 1987. In 1989 he joined to the Automatica Research Center of ENEL, where he worked as Researcher in the control system and voltage regulation department. In this period his main interest was in the field of simulation and real-time design, turbine and generator regulation, wind and photo-voltaic unit control. Then he worked at Enel S.p.A Ricerca from 1997, as Senior Researcher in the framework of grid voltage control (secondary and tertiary voltage regulation) and power electronics application (HVDC links, FACTS controllers). Since 2000 he is working at CESI as Product Leader within the Business Unit T&D Networks, in the framework of grid supervision and control. Author of about 20 technical papers on power system control.