Interconnection of Greek islands with dispersed generation via HVDC Light technology

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The Cycladic islands are today to a large extent locally supplied with oil fired power units and isolated from to the main grid. The Greek Authorities investigated alternative scenarios for supplying energy to the islands with a horizon up to year 2030. One of the scenarios is to connect the major islands in a power link utilizing HVDC technology based on voltage source converters. By connecting the islands to Lavrion, a sustainable power supply with low environmental impact will be achieved. In addition, the islands will benefit from a high security of supply and all local emissions on the islands will be eliminated.

Island infeed was first proven in 1954 in the Gotland project and subsequently in a number of installations worldwide. Technical development, within the area of HVDC, have enhanced the technical advantages for island infeed. The technical progress is based on new voltage source converters or HVDC Light (instead of the thyristor based classical HVDC technology). This new HVDC technology is an interesting system that addresses the challenges inherent with the long distance and high power demand on the islands.

This paper will deal with the main additional features of the new HVDC Light technology that could be enjoyed by applying this technology to the Cycladic project:

- HVDC Light´s voltage support capabilities shows in the preliminary studies to be essential to keep the voltage within desired limits in the ac distribution system.
- Supporting the parallel AC line from Andros, during steady state and dynamic disturbances respectively
- Possibility to support the AC system in Lavrion with reactive power to damp AC voltage oscillations
- Possibility to utilize the HVDC Light tie as the sole provider of energy to the islands without any local generation in operation at all.
- Black start capability and emergency power
- A robust polymeric HVDC cable system totally oil-free

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System overview

Figure 1. Greek island infeed

A proposed system utilizing Syros as the main infeed and distribution point is a feasible solution for electrification of the Greek island. An HVDC Light cable system (blue line) transmits power from the mainland, Lavrion, to the Island Syros. From Syros an ac cable (red lines) transmits power to Mykonos and another cable connects Syros with Paros and further to Naxos. Syros is also interconnected with the mainland existing network (yellow line) via Andros, so that a line loop is formed, that guarantees power infeed by two sources and that the n-1 criterion is fulfilled for all power connections.

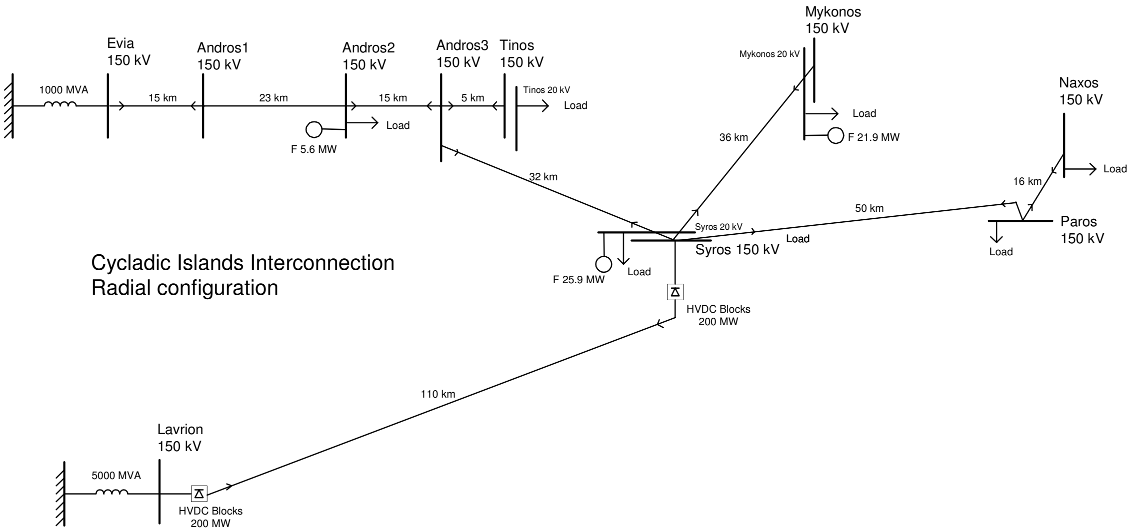

Figure 2. System configuration

The proposed system was studied [5] by taking into consideration the actual system data, the power demand evolution for a period up to year 2030, the existing and future possibilities for power generation and transmission systems infrastructure development and the overall investment costs, such as cost of energy, cost of financing, etc, as well as costs related to environmental constrains.

HVDC Light technology

ABB introduced 1997 a different HVDC technology from the present standards. It was called HVDC Light and is based on Voltage Source Converter transmission technology. HVDC Light is a concept of modern technology based on bi-polar converters and extruded DC cables with power units up to 550 MW. The differences between the Classic HVDC and the new VSC based technology may seem small at a first glance but have fundamentally different impact on the AC-DC interaction. The VSC solution gives many new possibilities to support the AC grid in addition to the power transfer itself. These possibilities reaches deep into traditional AC system operation.

HVDC Light operates via the DC voltage and is therefore a DC Voltage based transmission. With a DC voltage source and a fast switch that can turn on and off current available we can by switching between the two extremisms of DC voltage get on average any voltage in between. By applying special switching patterns we can generate a sinusoidal voltage. If this generated voltage is exactly in phase and amplitude with the receiving voltage will there be no power exchange at all. By slightly change amplitude or phase angle on the generated voltage we can start exchange both active and reactive power independently. The rectifier end now charges the capacitance. The layout is shown in Figure 3.

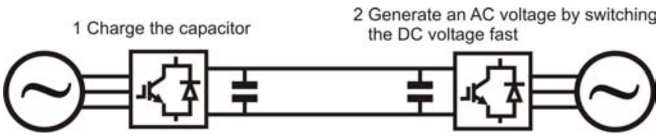

Figure 3 Simple model of HVDC Light

The resulting capability curve for HVDC Light will mainly be restricted by three factors that limit the capability seen from a power system stability perspective. The first one is the maximum current through the valves consisting of Insulated Gate Bipolar Transistors. This will give rise to a maximum MVA circle in the power plane where maximum current and actual AC voltage is multiplied. If the AC voltage decreases so will also the MVA capability.

The second limit is the maximum DC voltage level. The reactive power is mainly dependent on the voltage difference between the AC voltage the VSC can generate from the DC voltage and the grid AC voltage. If the grid AC voltage is high the difference between the maximum DC voltage and the AC voltage will be low. The reactive power capability is then moderate but increases with decreasing AC voltage. This makes sense from a stability point of view.

The third limit is the maximum DC current through the cable. The different limits are shown in Figure 4.

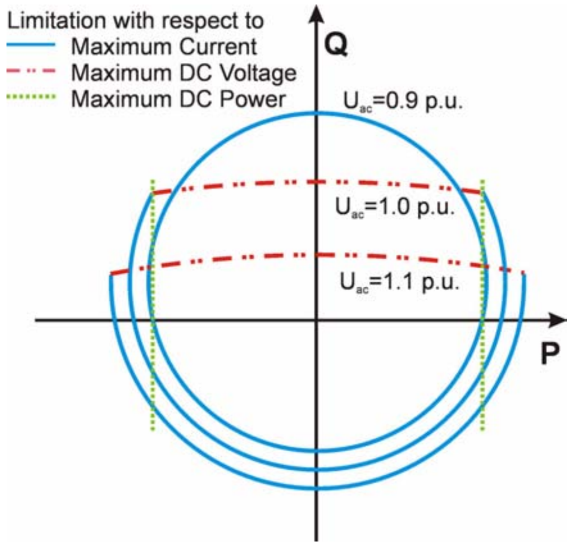

Figure 4. The capability curve for three AC voltage levels.

System stability

Voltage control

HVDC Light witch VSC technologies have the possibility to control reactive power, totally independent of the active power. This will give both stability and power quality improvements.

The HVDC Light converter can change from maximum capacitive to maximum inductive reactive power within a couple of milliseconds. The limitations for how fast the reactive power can be controlled are set by the surrounding AC system.

For a connection to a weak grid it can by an advantage to have fast AC voltage control to control reactive power used for voltage sags during fault in the AC grid. However, the normal voltage control operations have to be somewhat slower. An optimised voltage control can be achieved by an intelligent VAR control using special software algorithms to handle transient disturbances.

This has been implemented on Gotland HVDC Light by dividing the voltage control in control time aspects. For the fast transients, a special algorithm is defined to react on, for example, voltage sags. This is only in operation during a few milliseconds. After that, the normal voltage controller is active again. With this solution it is possible to have safe setting with high damping for the voltage controller and still have the advantages of fast voltage support during AC faults.

This voltage control and reactive power control philosophy could be a very useful tool in the Greek islands creating a stable AC system. Control features to create damping of voltage oscillations can be used to support the AC system both for the main land station Lavrion as well as for the island system in Syros. The load composition will vary between the Gotland and the Greek islands. For Greece is air conditioning load more frequent, thus the network is more exposed to transient voltage collapses. Fast access to reactive power is then crucial to mitigate these transient voltage collapses. The characteristics of HVDC Light where the output is only decreasing proportionally with voltage has very positive impact during a transient voltage instability.

Damping oscillations

The example below illustrates an HVDC Light link in parallel with an AC line. The simulation is shown in figure 5. A fault applied on 'node 1' is cleared after 100 ms. The rotor angle oscillations is presented for three different control strategies for the VSC transmission where the mixed control give the highest damping.

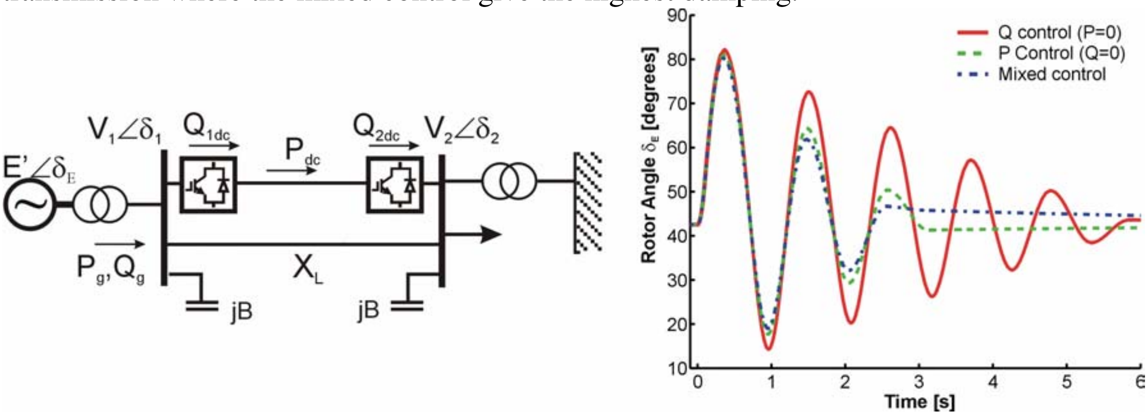

Figure 5 AC line fault cleared after 100 ms and the associated rotor oscillation for three different strategies for VSC transmission. Key grid parameters are X_L=0.5, B=0.2 (SIL=0.872 p.u.), H=4 and converter size=0.08 p.u.

The difference in damping between the methods will vary and a thorough investigation is necessary before the benefits for a specific project can be determined. For one parameter setup a mixed control with a third of the rating of Q control had the same damping i.e. a gain of 3. For another setup the gain was a factor 2. A more complex grid will have many aspects to consider before the actual benefits are established but VSC transmission systems do have a possibility to significantly improve damping for certain grid configurations.

A local generator on the islands may oscillate towards the grid on the mainland via Evia. HVDC Light has the potential to damp these oscillations. Implementing power damping controls in the HVDC Light could be advantageous to damp oscillations on the AC connection between the main land and Andros.

HVDC Light system stability on Gotland HVDC Light

HVDC Light in parallel with a weak AC network is powerful. It is possible to optimise the operation for both reactive and active power flow. The operation can be made automatically, only supervised from the control centre.

In Gotland HVDC Light it has been solved with cascade control. HVDC Light is parallel connected with the AC net and the AC net is very weak (Figure 5). The rated power for HVDC Light is 50 MW and the AC line has a capacity of 20 MW. The connected wind power productions capacity in the southern part in year 2004, was 48 MW.

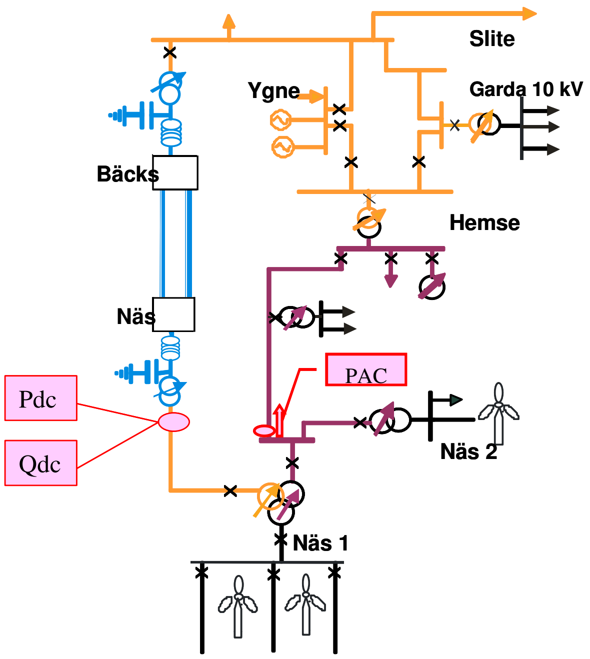

Figure 6. **Simplified diagram for Gotland HVDC Light**

To avoid overload in the AC line, the power flow is controlled by the cascade controller which decide the set or dispatch value in the power controller in HVDC Light. This controller operates autonomous locally which reduce sensitivity for communication disturbances. The connecting production of wind power has no forecasting for production and the power variation can be large. The settings has been adjusted in order to avoid any impact of dynamic phenomena and also to minimize tap changer operation in the transformers around the connection point. However, it can be fast enough to avoid an overload on the parallel AC line. The configuration, shown below, is similar to the Greek island case, where the same approach can be used.

Minimizing system losses

A slow, override control can be used in order to minimize ohmic losses in the system. On Gotland, the supervision uses three values for the transmitting system with HVDC Light. Those are MVAr in both stations and active Power for the AC line.
The SCADA system is calculating the set points by an algorithm that has been developed to minimize the losses in the whole system. The algorithm calculates values automatically to the HVDC Light for a period of 5 minutes. The dispatch centre only has to supervise the system and the operation is always been optimised and the losses will be minimized.

Robust system during contingences

For a parallel connection proposed for the Greek island, it is also necessary to look at the protection system, what happened if the AC line trip or other disturbances? Some simple new functions will be added for the AC line overload and for a trip of HVDC Light. If the

AC line trip, the HVDC Light will pick up the load and consequently saves the system in operation.
The voltage control and the protection give less stress on the AC grid. The power quality is also improved for the local load. This knowledge has been used to adjust the selectivity plans for relay protection with and without HVDC Light on the Gotland transmission. It has been possible to develop and implement such practical measures mainly due to the flexibility of HVDC Light.

Increased power on a parallel AC line

With this solution it has been possible to use the AC line much closer to the thermal limit. The application with HVDC in parallel gives this way also the benefit to use the existing AC line more with higher transmitting capacity. HVDC Light controlled as described it will be less stresses on the AC system
In the application for Greek islands this could be an interesting possibility to maximise the utilisation of the existing AC line from Andros.

Island operation with HVDC Light

An interesting feature of the HVDC Light converter is the possibility of supplying a passive network without its own generation. With supply to a passive network the static converter controls the AC voltage with regard to amplitude and frequency. This function is to be utilized in the Tjäreborg and Eagle Pass HVDC Light transmissions. Such a function can be of importance even if the HVDC Light system is connected to an active AC-network, as it may become islanded and passive during contingencies. An island part of the AC-system can occur if a nearby AC-breaker opens up due to fault indication. The HVDC Light system can be programmed to switch from active power order to frequency control from a last breaker opening indication or by under or over frequency indication.

This could mean that for the Greek island that in case the AC transmission is lost between the mainland and Andros the HVDC Light system can automatically compensate for the power loss and keep the AC system in operation.

Black start capability and emergency power

A VSC transmission system will be a valuable asset during a grid restoration. It will be available almost instantly after the blackout and does not need any short circuit capacity in order to become connected to the grid. The benefits will differ if one or both ends are exposed to the blackout. The following list highlights some aspects:

- Black start capability if equipped with a small diesel generator feeding auxiliary power (or power from another grid).
- Fast voltage control is available in both ends virtually instantly after the auxiliary power is back.
- Can energize a few transmission lines at a lower voltage level avoiding severe Ferranti-overvoltage and allow remote end connection of transformers/reactors at a safer voltage level. When the remote end is connected to the reactor/transformer the voltage can be ramped up to its nominal value.

- When active power is available in the remote end the VSC connection can feed auxiliary power to local plants making sure that they have a stable voltage/frequency to start on.
- When the local plants are synchronized to the grid they can ramp up power production at a constant and safe speed and do not initially have to participate in frequency control. Thermal time constants and control issues in the boiler can then be handled. The VSC transmission system is taking care of frequency variations via power exchange to the remote grid. This will increase the likelihood of a successful startup. Islanding operation of a single power plant is seldom tested beforehand and the operation is therefore not reliable. The VSC transmission system does not have thermal/mechanical systems that are affected by rapidly changing active power demand and will therefore be a safer and tested way to use for frequency control. It can also temporarily export power from the island. Meaning that we can have a considerable overproduction available in the island before we start to connect load.
- When the power production margins are safe we can start connecting load. The system is now ready to handle phenomena as cold load pickup and varying AC voltage in the transmission grid. More generation is fed with auxiliary power and then connected.
- Classic HVDC can be started when the short circuit capacity is sufficient.

The buildup scheme has the potential of being quite robust and fast. Especially if the remote HVDC Light system end is connected to a strong grid. Speed and robustness during the buildup could be valuable from a socio-economically perspective. With a HVDC system, the blackout period could be reduced to 15 minutes compared to an average build up time of 6 hours.

Protection coordination

The HVDC Light system has the advantage of not contributing to the short circuit currents in the connecting system, thus there will be no need for upgrading circuit breakers. However, this has to be addressed when discussing protection coordination.

For the selective scheme of the system it is important to consider the dynamic properties for HVDC Light, especially when the HVDC Light is connected to a weak grid and necessary with Island operation with HVDC Light.

The response from HVDC Light during an AC fault is rapid, but the maximum current is limited close to the rated current. Comparison with a synchronous generator with the same rated power, the fault current is lower. The settings for the overcurrent protections close to the HVDC Light converter station should be investigated.

Dynamic studies have been performed in the Gotland HVDC Light project in order to verify the protection coordination. The conclusion was that only one relay had to be changed to impedance detecting function. The remaining relays were simply coordinated by adjusting the settings.

Environmental issues

- The converter station is of an indoor type, it resembles a normal building and will assimilate well in the surroundings
- More efficient power supply from the mainland's generation mix, replaces oil fired power stations on the islands, with the result of a reduction of CO_2 emissions in Greece
- The submarine HVDC cable will continue underground on shore, i.e. no overhead HVDC lines on any site, i.e. minimal visual impact

HVDC Light submarine cable

HVDC Light Cable is a cable with extruded polymer insulation and specifically adapted for direct voltage. The strength and flexibility of HVDC Light Cables makes them well suited for severe installation conditions both as an underground land cable and as a submarine cable. HVDC Light therefore provides the ideal medium for transmitting power over any distance underground or under the sea.

New applications with polymeric HVDC Light Cables

Compared with traditional paper insulated cable, the polymeric cable has a number of advantages due to its excellent mechanical strength and flexibility. These advantages allow the use in areas of;

- Steeps (e.g. offshore platform risers)
- Extreme water depths
- Tough installation conditions
- Dynamic movements (vibrations)

Submarine reference installations for HVDC Ligh®t cables

Installation at the Troll A platform, Norway

The submarine HVDC Light cables for the two 40 MW drives consists of 4 nos. of single conductor cables. All are installed in the same 423 m long J-tube from just above the sea bottom at 300 m water depth to level 30 m above the sea level on the platform. The cables, loaded on the cable laying vessel, were pulled simultaneously in through the J-tube, hung-off at top and sealed off at both top and bottom of the J-tube. The J-tube was then filled with an inhibitor fluid to prevent corrosion. In order to limit the pull break force in case of fishing trolleys or boat anchors hooking on to the cable package, the hang-off is equipped with a weak link disrupting at 250 kN.

The remaining installation was performed by conventional submarine and land installation methods.

The cable installation in Long Island Sound, USA

The two HVDC Light power cables and the multi fiber optic cable were laid bundled together to minimise the impact on the sea bottom and to protect oysters, scallops and other living species.

The cables were buried six feet into the sea bed to give protection against fishing gear and anchors.

Low magnetic fields from HVDC Light Cables

The HVDC Light Cable System has the advantage, due to its bi-polar construction, of virtually eliminating magnetic radiation generated from the current in the conductors. This feature is of great importance for obtaining required permits from environmental agencies.

Conclusions

The interconnection of the Cycladic Islands via an HVDC Light power link will introduce additional features for the system operator and the local societies enabling them to:

- Maintain an acceptable voltage profile throughout the island's AC distribution system
- Support the AC system in Lavrion with reactive power
- Provide black start and emergency power capabilities
- Fulfill the environmental constrains and enhance wind power penetration.

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