Proceedings of the 5th WSEAS Int. Conf. on Power Systems and Electromagnetic Compatibility, Corfu, Greece, August 23-25, 2005 (pp429-435)

Interconnection of the Cycladic Islands to the Mainland Grid

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Abstract: - In this paper the main results of a study concerning the optimum solution for the electrification of the Cycladic islands, in a long term period, are presented and discussed. There are three main Scenarios: (A) the extension of the existing interconnection to the main land grid and development of local diesel power stations, (B) the construction of a new interconnection to the main land, (C) the development of the existing and new diesel power stations. A brief presentation of the possibilities offered by the recent technological progress on the submarine transmission that are taken into account in the study is also made. The three Scenarios are compared from the technical and economical point of view and their main advantages and disadvantages are discussed.

Key-Words: - Submarine cables, electrification of islands, AC and DC transmission, diesel power stations in islands, renewable energy in islands.

1 Introduction

The generation of electricity in islands is generally made using expensive oil products. Consequently, their interconnection to the large power system of the mainland by submarine cables presents considerable economic interest. At the same time, the interconnection creates the opportunity for better exploitation of the favorable wind potential existing on many islands.

Currently, all large islands of the Ionian Sea in western Greece are already connected to the mainland grid by 150 kV submarine cables. Several interconnections at 20 kV also exist, mostly in the Aegean Sea, in the case of islands with relatively low maximum demand, which are situated near the mainland. More specifically, 32 islands in total are interconnected to the mainland system by HV and MV submarine cable lines, whereas the same number of islands are interconnected to each other, but not to the mainland grid. The HV (150 and 66 kV) and MV (20 and 6.6 kV) submarine cable interconnections respectively exceed 70 km and 1000 km in length.

The interconnection of the Cyclades islands to the mainland system has been partly realized and it is currently under study to be expanded to include most major islands of the region. It presents a special interest because of the large length of the cable lines involved and the considerable electric power demand of particular islands and the group in total. In this paper, after a short presentation of the "state of the art" on the submarine transmission of electrical power, the main results of a recent feasibility study for the Cyclades interconnection are presented and discussed.

2 Technological progress on submarine transmission

2.1 General

The minimization of the length for HV AC submarine cables has been the principal concern in the design of submarine cable interconnections, for two main reasons:

-**Technical**: due to the large capacitance of the HV cables and the reliability concerns for the multiple cable joints.

- **Economical**: due to the high investment cost of the sub sea cable lines, compared to the standard overhead or underground cable lines.

Until recently, the maximum acceptable length of HV submarine AC cable lines was about 60 km and the applied technology was paper-insulated oil-pressure single-core cables. During the last years an increasing interest exists for relatively long AC or DC transmission lines for the supply of offshore oil platforms and more recently for the connection of large offshore wind parks to the mainland power system.

2.2 AC transmission

It is well known that the synthetic (XLPE) insulated cables dominate in the construction of HV land cable lines, because of important advantages compared to the older paper-oil insulated cables: avoidance of hydraulic systems, smaller capacitance and weight, ease of installation etc. However the use of XLPE insulation in submarine cables has been restricted to land applications until today, mainly due to the difficulty to construct long one-piece cable lengths and the ensuing need for multiple flexible factory joints, [2]. The HV land cables are usually single-core, installed in flat or trefoil formation. Single-core submarine XLPE cables are also used, but it appears that the three-core design with water impervious barriers (sheaths) on each core is preferred, [2, 3].

The reactive power compensation for HV AC cables is usually realized by fixed or electronically controlled shunt reactors at both terminals. The progress in the Static VAr Compensators, with SVC or STATCOM capabilities, considerably extends the reactive power and voltage control possibilities offered by the switched shunt reactors and capacitors. This compensation may fulfill different complex functions, such as steady state reactive compensation and dynamic voltage control, improving voltage regulation and the transmission capability of the AC interconnection.

2.3 DC transmission

HVDC transmission technology has been applied for many decades now for the interconnection of strong AC power systems, using Line Commutated Converters (LCCs). Recent progress in the technology of the power converters has permitted the extension of the DC transmission technology for feeding remote, isolated AC networks, without need for installing sources of commutating capacity in the remote AC network (e.g. large rotating synchronous condensers), [2]. This was realized by application of Voltage Source Converters (VSCs) for DC voltages up to +/- 150 kV, instead of the Line Commutated Converters with thyristors used for the interconnection of large AC power systems. This evolution is due to the rapid development of fast power electronic switches with turn off capability, like the GTO thyristors and currently the IGBTs.

In Fig. 1 and 2, one pole of a conventional and a VSC-based HVDC transmission scheme is shown. An identical station would exist at the other end of the DC circuit. The main components of each station are the transformers, the AC filters, the converter valve groups, the DC-side reactors capacitors and the control system.

Mass-Impregnated type cables are normally used in HVDC systems. However extruded cables with polymeric insulation have been also developed and are now used in VSC-based schemes. This is partly due to the fact that the VSC technology makes unnecessary to change polarity of the DC voltage when reversing the power flow direction.

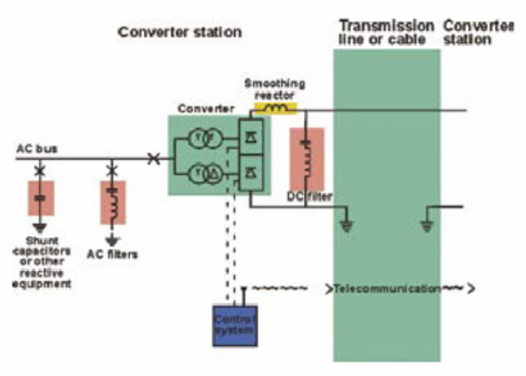

Fig. 1 Simplified diagram of one pole of a conventional HVDC transmission scheme.

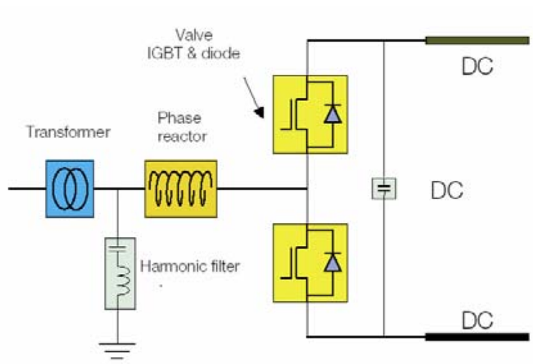

Fig. 2 Simplified diagram of one pole of a VSC-based HVDC transmission scheme.

2.4 Advantages-Disadvantages of the AC and DC transmission systems

It is well known that the HVAC transmission length is limited, due to the cable charging current, the magnitude of which depends on the type of insulation, increasing also with voltage level and the length of the line. In recent years AC submarine

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cable systems up to 170 kV with XLPE insulation have been developed, [1-3]. Due to its lower dielectric constant, the XLPE insulation presents lower charging currents per unit length than the earlier used paper/oil insulation materials. Maximum power transmission is determined by voltage regulation (usually up to of the nominal) between no load and maximum load at either end, while the current remains below the thermal limit throughout the cable length. The optimum situation is reached when the current in the cable is compensated equally at each cable length. In a recent paper ([2]) it is stated that the length of an 150kV, 3x1x1000mm2, properly compensated, XLPE submarine cable line, can exceed 200km, transmitting more than 200MW, [2].

In DC transmission the length and the power may be higher than in AC transmission and the DC transmission may offer higher control capabilities and voltage. Single-core DC cables are also much simpler and lighter than the corresponding AC ones. Consequently, DC transmission becomes more cost effective in relatively long distances, taking into account that the cost of the converter stations is fixed (independent of the distance).

Losses in AC systems are about 0.2-0.3% of the rated in the transformers, approximately 0.3% in mechanically switched shunt reactors and less than 0.9% in SVCs at full reactive power mode. The main losses in AC cables are the ohmic losses in the current currying conductors. Losses due to eddy currents in the sheaths and the armour depend on the design of the cable and are considerable higher in single- than in three-core cables. The losses in VSCs are less than 3% (including their transformers). Losses in the DC cables are ohmic in nature, caused by the DC current in the conductor. The dielectric losses are generally negligible for operating voltages up to 150 kV.

3 The case of Cyclades islands

3.1 The existing situation

The Public Power Corporation of Greece decided in 1989 to interconnect the Cycladic islands Andros, Tinos, Syros, Myconos, Paros and Naxos to the mainland grid via Evia, as shown in Fig. 3. This decision was based on a long-term study, covering the period 2000-2025. The interconnection was designed according to the usual practice at that time, as indicated in Fig.2, that is ([4]):

- The connection was made to the nearest mainland point, at Evia. All submarine connections were designed for minimum cable length. HV overhead lines were foreseen to cross the islands.
- For the connections of Evia-Andros and Andros-Tinos the design was for 150 kV submarine cable lines with 4 single-core paper-oil insulated cables (one for each phase and one spare). Three-core 66 kV mass-impregnated paper insulated cables were foreseen for the connection of the other islands, to reduce the reactive compensation needs.
- One 150/66 kV substation was scheduled for Tinos island and one 150 or 66/20 kV substation on all other islands.
- The existing diesel power stations should be reinforced and a provision was made for a large new diesel power station on Naxos.

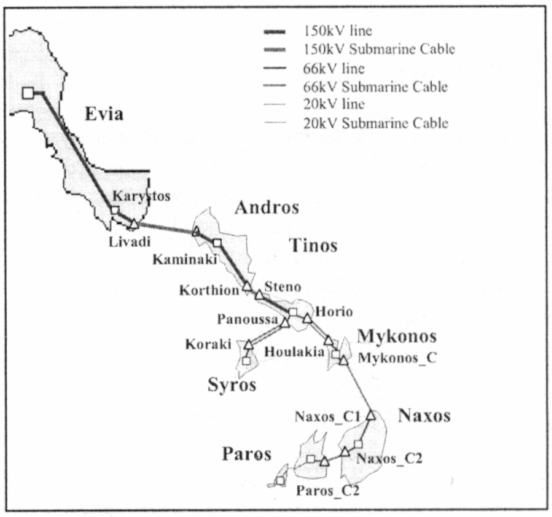

Fig. 3. Initial planning for the interconnection of the Cycladic islands.

The maximum capacity of the 150 kV interconnection is 125 MW, while the forecasted maximum demand at year 2025 was 225 MW. Hence, a total local generation of about 150 MW (from existing and new diesel power stations) was needed in order to partially cover the local demand in case of loss of the interconnection to the mainland.

Strong reactions of the local communities and subsequent court decisions, ruling against the construction of overhead HV lines on the islands, permitted construction of the HV overhead lines only up to the 150/20 kV substation on the island of

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Andros. Although the 150 and 66 kV submarine cables were installed without problems, since 1993 they are operating at 20 kV, as a part of the local distribution network. At the same time, to satisfy the fast increasing demand, new capacity is being added to the existing diesel power stations.

3.2 The new interconnection planning

To deal with the situation developed, a new long term study, covering the period 2010- 2030, was assigned to the National Technical University of Athens, whose the main points are presented in the following.

3.2.1 Estimated load growth

The estimated load growth for each island is shown in the Table 1. It is very close to the load growth taken into consideration in the previous study of PPC, [4]. Since the diversity of the maximum demand among the islands is negligible, the peak load of the whole group can be obtained by summation of the individual peaks.

Island	2010		2020		2030	
	MW	GWh	MW	GWh	MW	GWh
Andros	9,00	50,2	26,0	75,3	35,0	101,1
Tinos	8,00	44,8	24,0	66,1	32,0	89,0
Syros	30,6	147,4	45,3	218,2	61,0	293,3
Myconos	39,4	138,0	48,0	168,2	58,5	205,0
Naxos	40,0	140,0	59,0	207,0	79,3	278,2
Paros	42,2	148,0	62,5	219,1	84,0	294,4
Total	169,2	668,4	264,8	953,9	359,8	1261,0

Table 1. Estimated peak load and annual energy demand growth for the Cycladic islands.

3.2.2 Selected Scenarios

Objective of the new long-term planning was the selection of the technically and economically optimum development of the electrical system of the Cyclades islands, taking into account:

- The capabilities offered by the technological evolution in submarine power transmission, to minimize environment impacts, ensure acceptance by the local communities and avoid prolonged court fights.
- The existing power system installations and infrastructure.
- The need for facilitating the development of the excellent wind power potential of the islands, as well as of the geothermal potential of the nearby island of Milos.

Fig. 4. Scenario A: Interconnection to Evia and development of local power stations.

Fig. 5. Scenario B: Interconnection via Lavrio and Evia.

After evaluation of a large number of candidate solutions, the following three were analyzed in detail:

Scenario A: Connection to the grid only at Evia (A1: by the existing single-circuit lines or A2: by their upgrade to double-circuit) with the gradual development of the diesel power stations, so that the local demand and the necessary reliability of supply are met, Fig. 4.

Scenario B: New connection to the mainland grid at Lavrio (main in-feed point), in addition to the existing at Evia, and elimination of the diesel power stations, Fig. 5.

Scenario C: The connection to the mainland grid is restricted only to the existing line from Evia. Only the islands of Andros and Tinos are connected to the mainland, while the remaining four islands form two separate isolated systems, Syros-Myconos and Paros-Naxos, by development of local diesel power stations.

In all Scenarios the following design principles were adopted:

- The construction of new HV overhead lines on the islands shall be avoided. For this purpose, the landing point of the submarine cables and the corresponding 150/20 kV substation will be located near the “load center” of each island, as indicated in Figs. 3 and 4. Construction of indoor substations with 150 kV GIS switchgear is foreseen, to minimize land use requirements.
- The “N-1” supply reliability criterion should be satisfied in any case, that is the supply should be assured in case of failure of any single element of the power system.
- AC or DC technology is accepted for the connection Lavrio-Syros, where the distance is about 100 km and the maximum transmitted power for the end year 2030 is estimated to be 320 MW. All other submarine interconnections between islands, where distances do not exceed 50 km and transmitted powers are up to 200 MW, are AC interconnections. One or three-core 150 kV AC cables are accepted. XLPE insulated cables are foreseen, properly compensated at their ends by shunt reactors or SVCs, so that the voltage variations do not exceed of the nominal voltage.
- In order to satisfy the N-1 criterion, four one-core or two three-core cables are utilized for radial lines. In case of meshed network formations, one three-core cable per line is accepted, Fig. 5.

To make all Scenarios comparable from the point of view of environmental impact and public acceptance, it was considered that the interconnection between islands by submarine cables and the substation sites will be the same, as indicated in Figs. 4 and 5. The economic evaluation of each Scenario was made in the standard way, by calculating the NPV at year 2004 of all future expenses (investment costs, operating and maintenance expenses, fuel costs, interconnected system energy costs).

3.2.3 Presentation of the Scenarios

Scenario A:

It is obviously an adaptation of the existing planning, in order to fulfill the requirements set. Two alternatives were analyzed for this Scenario:
A1: The interconnection to the grid remains in its current state, consisting of single-circuit overhead 150 kV lines on Evia and Andros, with a maximum capacity of 125 MW. To cover the additional load demand and to satisfy the N-1 criterion, it is necessary to maintain local power generation of about 170 MW on 2010, 240 MW on 2020 and 320 MW on 2030.
A2: The interconnecting overhead lines and cables on Evia and Andros are upgraded to double circuit. Then, 125 MW are always ensured from the grid (in N-1 conditions) and the required local generation for Scenario A1 is reduced by this amount of power.

Scenario B

In this Scenario a new connection to the mainland grid is realized, from Lavrio to Syros, at the center of the Cyclades. Since Lavrio is one of the large natural gas-fired power stations of the Greek interconnected power system, the availability of the power required for the Cyclades is assured. With the current state of the art, discussed in Section 3.2, a direct connection Lavrio-Syros, with a 350 MW transmission capacity over a distance of 100 km, can be realized by AC or DC transmission technology. This link will constitute the backbone feeder for the Cyclades islands and it is expected to operate in parallel to the existing connection to Evia, with either AC or DC technology.

If an AC link is preferred for the Lavrio-Syros interconnection, it may consist either of two separate three-core cables or of four one-core cables, in order to satisfy the N-1 criterion. In case of a DC interconnection, two parallel half-capacity circuits, like the one shown in Fig. 1, are necessary for the same reason. Both solutions are acceptable, although the DC transmission may offer additional advantages in case a large amount of wind power is installed on the islands, as it will be discussed later. It is also possible to delay the installation of the second parallel circuit, e.g. up to 2020, assuming that the existing diesel power stations can offer the required power reserve during this period. In any case, a further analysis of the whole subject of the Lavrio-Syros interconnection is necessary, taking account actual costs that were not available with sufficient accuracy at the time of the study. In the case of AC transmission, the small islands of Kea and Giaros can serve as intermediate landing points, in order to break the whole Lavrio-Syros interconnection in three short sections. In this way, along with the intermediate compensation of the submarine cables, the connection of these islands to the grid is also achieved.

Scenario C

This scenario requires the development of significant local generation:
(a) In Syros-Myconos: 90 MW on 2010, 125 MW on 2020 and 140 MW on 2030. The two islands will be interconnected at 66kV.
(b) In Naxos-Paros: 110 MW on 2010, 160 MW on 2020 and 180 MW on 2030. The two islands will be interconnected also at 66kV.

The realization of this Scenario is uncertain. The main difficulty is that the existing diesel power stations are situated near residential areas and consequently their further extension is not possible. On the other hand, because of the touristic character of the islands, it is very difficult to obtain permits for developing new power stations. In any case, Scenario C was included in the study mainly to estimate the total cost of this solution, to serve as a basis for comparison with the other two Scenarios A and B.

Alternative solutions

a) For the island of Tinos, where 150 kV works have already started and the 66 kV submarine cables to Syros and Mykonos have been installed, various alternatives were considered. One is to avoid construction of any new HV line on Tinos and feed it at 20 kV via the installed submarine cables from Andros, Syros and Mykonos. Another is to construct the 150 kV overhead line and a small 150/20 kV substation for the local loads (if permits are obtained), as indicated by dashed line in Figs. 3 and 4.

b) Instead of the interconnection via Lavrio-Syros or Lavrio-Kea-Giaros-Syros, the interconnection Lavrio-Kea-Serifow-Sifnos-Paros and Milos by AC cables was also extensively examined. It was found that, because of the large number of successive cable connections the voltage regulation presents many problems and requires a large number of compensation means. The islands Serifos, and Kythnos could be connected by 20kV cables, after the connection of the Milos - Sifnos, to the system.

3.3.4 Comparison of the scenarios

Evaluation of Scenarios A to C was performed by comparison of their total cost, their impact on the environment and the estimated public acceptance, the possibilities offered for the development of local renewable energy sources, the security and quality of supply offered to the consumers and the facility of operation. The results of the study are summarized as follows:

(a) Total cost
The cost of each Scenario, expressed in values of the year 2004, is as follows in Table 2:

Scenario	A1	A2	B	C
Availability of diesel units	174	311	67	414
Investments	152	125	278	
Energy cost	443	437	443	363
Total	**769**	**874**	**788**	**777**

Table 2: Cost analysis.

That is the total cost of Scenarios A2, B and C is practically the same, while the cost of the Scenario A1 is about 14% higher.

(b) Environmental impact and public acceptance

Scenario B is clearly superior to all others, given that the sole impact comes from the construction of the GIS substation buildings near the landing points of the submarine cable lines.

(c) Possibilities for development of local renewable energy sources

Local renewable energy sources include the excellent wind potential, existing in all Cycladic islands, and an important geothermal potential suitable for electricity generation on Milos island, estimated at about 120 MW.

The wind power that can be installed on the islands is mainly limited by land use and availability issues. It is estimated that a power of the order of 150-200 MW could be installed in total. This wind power can easily be absorbed in the case of Scenario B, as well as in case of Scenario A, with certain additional difficulties (a further investigation is required on this subject). On the contrary, this amount of wind power cannot be absorbed in the case of Scenario C, given that the maximum installed wind power in isolated power systems cannot exceed 20-30% of the annual maximum demand.

With respect to the geothermal potential on Milos, it must be taken into account that its proper exploitation requires operation of the geothermal power station at approximately constant loading conditions. This can be achieved with Scenarios A and B by the direct connection of the geothermal power station to Syros, as indicated in Figs. 3 and 4. In Scenario C, it would be necessary to make the connection directly to the mainland, eventually by DC, or to restrict the exploitation of the geothermal field by its adaptation to the needs of the neighboring islands (e.g. by connection to Naxos). In any case this subject requires also a further investigation.

(d) Security and quality of supply

All scenarios were properly analyzed, to ensure that they satisfy the operating voltage limits and thermal capacity constrains of all lines. However, a weak point of Scenarios A (A1 and A2) is their reduced reliability, compared to the two other alternatives: For any fault (permanent or transient) on the 150 kV overhead lines on Evia and Andros (about 130 km long), a total or partial black-out may occur if the local power stations operate in parallel to the system. The extent of the disturbance obviously depends on the local power in operation at the instant of the fault (diesel and renewables), the operation of the protections and the time to start the required amount of local diesel generating units, in case of permanent faults.

4 Conclusion

The large progress achieved during the last years in submarine power transmission technology considerably extends the possibilities of interconnecting isolated island grids to the mainland system. In the studied case of the Cyclades islands, currently fed by local diesel power stations, it is clear that the application of these technologies can greatly reduce any environmental impacts, improve the quality of supply and facilitate the development of local renewable energy sources, without significant additional costs.

Among the electrification alternatives examined, Scenario B appears to be clearly superior to the others. Steps to follow for the implementation of this Scenario include first the determination of landing points for the submarine cables and sites for building the 150/20 kV substations, as well as the restructuring of the MV distribution networks on the islands.

Further investigation is also required for the behavior and stability of the system in transient conditions. This will involve the control and protection of the VSC, in case of a VSC-HVDC interconnection to Lavrio, and will also take into account the expected high wind power penetration and possibly the operation of the geothermal plant at Milos.

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