PLANNING OF DISTRIBUTION NETWORKS IN HIGH WIND PENETRATION AREAS USING GIS FACILITIES

N.G.Boulaxis boulaxis@power.ece.ntua.gr
M.P.Papadopoulos mppapad@power.ece.ntua.gr
National Technical University of Athens
Department of Electrical and Computer Engineering
Electric Power Division
42, Patission str., Athens, Greece
Tel. +30-1-7723967, Fax: +30-1-7723968

G.Glinou
glinou@cresdb.cress.ariadne-t.gr
Center of Renewable Energy Sources
Wind Power division
19o km, Marathona str.
190 09 Pikermi, Attiki, Greece
Tel. +30-1-6039900, Fax +30-1-6039905

ABSTRACT

The Geographical Information Systems (GIS) are extensively used during the last years by Local Authorities and Utilities, because they offer the advantage of handling and processing different types and large amounts of data. In this paper, a GIS based method and the main features of the corresponding software are presented, for the optimal integration of Renewable Energy Sources (RES) in the electric power grids. The method takes into account the geographical data available in the GIS data bases on a local level, along with the necessary RES data (e.g. wind speeds or solar radiation intensities) and network data (lines, loads etc). The objective is to select the most cost effective among the RES considered and the technologies and determine the way of their connection to the distribution network, as well as the optimal network extension.

1. INTRODUCTION

It is expected that the Renewable Energy Sources (RES) capacity connected to the power systems, will increase considerably in the next years. For the time being, the most promising of the RES is the wind energy generation, but other solar-based technologies (e.g. Photovoltaics) are in development.

The connection of dispersed Wind Turbines (WTs) is usually made to the Medium Voltage (MV) network using dedicated step up transformer, since commercial sizes nowadays exceed 300kW. Nevertheless, Wind Parks (WPs) of a total power exceeding 10MW is a common practice, requiring extensions of the High Voltage (HV) network, or at least dedicated MV feeders at the HV/MV substations [1]. On the other hand, the main characteristic of the RES, especially the wind power, is that the produced power varies in a random way. This influences considerably the load flows at different parts of the network and consequently its operation and planning [2].

In this paper, a method and the main features of the developed software are presented, for the planning of distribution networks in areas with high wind penetration, using GIS facilities. Taking into account the geographical data available in the GIS data base on a local level, along with the necessary RES data (e.g. wind speed or solar radiation) and the data concerning the electric network and the loads, the method searches for the optimal integration of the RES in the electric power systems. Although the methodology and the case study presented in the following considers only WTs, dispersed or concentrated in WPs, it can be easily extended to include other types of RES and their combinations.

The developed planning algorithm has two main stages:

- In the first, the data base is constructed and a preliminary analysis using the GIS facilities is performed.
- In the second stage, the optimum planning of the network is studied, for short and long term periods.

The method is applied to an extended region of the south-west Peloponnese, in Greece, where favorable wind conditions exist, and the main results are shortly presented.

2. PRELIMINARY STUDY

At a preliminary stage, the GIS is used to determine the areas presenting considerable interest for RES development.

a) According to the GIS practice, the total area is divided in “pixels”, that is, elementary rectangular areas of the same land use. For each pixel all the information relevant to the feasibility of power production from RES and the electric network is included in the data base. The dimensions of each pixel are selected in such a way that the minimum power of the RES units under consideration, can be installed. The pixels can be classified taking into account different criteria (land use, surface slope etc.), in order to exclude some of them which cannot be candidate RES or substation sites.

b) Groups of a preset number of pixels, required for the installation of a composite RES (eg. a WP), can be formed and classified, using different criteria.

c) The annual energy production expected by each composite RES can be calculated. E.g. in the case of WP, this is done taking into account the annual wind speed distribution and the power curve of the WTs to be installed in the WP. Steps (b) and (c) are realized by software developed for this purpose.

d) All information concerning the electric power network of the region is also included in the GIS (lines, substations, loads etc).

3. OPTIMUM NETWORK PLANNING

This is realized in two stages:

- Integration of the RES by rearrangement and expansion of the MV network
- Optimum development of the HV and MV network, considering a multiyear planning period.

3.1 Integration in the MV Network.

This is performed in the following steps:

(a) Considering the existing electric network without its normal loads, the developed computer program indicates the locations where the minimum unit power of the RES can be installed and calculates for each pixel the corresponding Levelised Energy Cost (LEC), that is the per unit production cost (e.g. ECU/kWh). This cost is calculated taking into account the expected amount of electric energy that can be produced annually and the annual cost of RES, including equipment, erection and connection to the nearest point of the network, so that the preset technical constrains are satisfied.

The output of the analysis of this step is a list of pixels sorted in ascending order of their LEC value. By selection of a minimum acceptable LEC, the pixels presenting an economic interest are determined and presented in colored maps produced by the GIS. These maps give the overview of the most favorable areas for the development of specific RES, within the investigated area

Groups of N neighboring pixels are considered to form a region where a WP of a given installed power P can be installed. E.g. N=5 pixels, containing one WT of 500kW each, are required for the development of a P=2.5MW WP. Next, the annual energy that is expected to be produced by the WP is calculated adding the separate production of each pixel, and the LEC is subsequently calculated, taking into account the cost of the connection to the network, as well.

(b) For the connection of each one WP to the grid, the minimum cost solution is selected, subject to predetermined technical constrains, such as voltage deviations (slow and fast), thermal limits, etc are satisfied.

The following possibilities (solutions) of connection to the grid are examined in the algorithm:

(i) Connection to the existing MV network. The connection point is selected scanning all network nodes, starting from the nearest one, and advancing gradually towards the HV/MV substation, until the technical constrains are satisfied. If the HV/MV substation is reached, then a dedicated line is required for the connection of the RES and the cost of the MV switching equipment is added to the cost of the line.

(ii) Connection by more than one dedicated MV lines, departing from the HV/MV substation. In this case a maximum number of these lines has to be specified (usually up to five).

(iii) Connection by the extending the HV network and constructing of a new HV/MV substation, near the RES site.

In the above analysis distribution network loads can be taken into account in different ways. Already connected RES, can also be considered.

The output of this step is a list of the regions, consisting of N adjacent pixels each. The regions are sorted by ascending order of their LEC value. All the required details, such as the way of connection to the grid and the resulting voltage changes, the produced energy, the costs, the pixels coordinates etc, are also calculated. The first M regions and the corresponding WPs in decreasing LEC order, are selected and stored. E.g. a list consisting of M=20 regions, where WPs of 5000kW can be installed.

(c) Prior to any decision of extension of the HV network, the capability of the existing MV network to accept the selected RES is of interest to be determined. The method takes into account the RES already connected to the grid and re-determines the next one, in order to obtain the minimum LEC. A possible change of the LEC will be due to the new way of connection that may be required, for technical reasons. In the loading conditions of the network assumed in this step, any other type of RES already connected to the network can be considered, besides the normal loads.

(d) In case that an extension of the HV network, appears to be technico-economically most effective - case (iii) - then, a further investigation, as described in the next paragraph, is necessary. Nevertheless, before this investigation it is reasonable to seek a more clear view of the impact because of the RES connection. More specifically, the operating network conditions under maximum and minimum annual loads are considered in the previous analysis, with the RES operating under extreme power conditions. In order to obtain a complete picture of the impact from the connection of RES to the network, time series of the loads and the RES production can be used in order to calculate “quality indices”, e.g. according to EN 50 160.

3.2 Multiyear Planning

In case of HV network extension (construction of new HV/MV substations and HV lines), the development of the loads and of the RES in the studied region must be taken in to account, for a period of several years (e.g. 5 to 10 years). Although well established load forecasting techniques exist, it is much more difficult to estimate the development of RES, because it depends on factors such as the policy of the state against RES, the diverse development of their technologies etc.

A plausible approach is to consider different scenarios of RES development, assuming that their installation starts at the regions where they are more profitable. For this purpose the preliminary analysis described in section 2 may be used. For each scenario, the development of the RES and the loads are considered to be known on a yearly basis for the whole study period (e.g. the next 10 years). The developed computer program determines the new HV and MV lines and the new HV/MV substations (position and size) to be constructed in each year, as well as the optimum MV network rearrangement and loading, so that the minimum total cost is achieved.

The main features of the developed algorithm for this purpose are the follows:

(a) The last year of the study period is considered, in order to have an estimation of the number of the finally required new HV/MV substations and select the candidate sites. For this purpose, the construction of one or more (up to a prefixed number) of new HV/MV substations is considered. The candidate sites and the service area of each new HV/MV substation for the last year are selected so that they are in the gravity center of the served loads, while the voltage drop and thermal constraints are satisfied. This is made as follows: first the service areas of the existing substations are extended to serve the (electrically) nearest loads, while the voltage drop and thermal limits are satisfied, up to their nominal capacity or another predetermined power limit. The maximum loading of each substation is taken either the maximum value of the "load power" or the "renewable power" alone, or as their complex sum. The remaining loads and RES, have to be connected to the new substations. Next, the gravity centers of these remaining loads (including RES) are found. The procedure is based on replacing pairs of loads by their "equivalent load". The procedure starts with the two most neighboring loads and is repeated until the prefixed number of substations is reached. In each step, the equivalent load is equal to the sum of the pair of loads, placed on their "gravity center". The prefixed number of the candidate HV/MV substations, in site and composition, are located in the finally determined "gravity centers".

(b) For each new HV/MV substation the algorithm provides its connection to the existing network by new MV lines. The connection is considered by a switch, to a proper point (usually to the nearest node of the main part of the feeder). Connection to the HV network is also considered. Moreover, the new loads and RES, are connected by new MV lines in the proper MV network point. Finally, the optimum MV network rearrangement, for each year of the study period is performed, [3,4].
Consequently, for this particular HV/MV substation arrangement a set of several network configurations is formed for each year. Each HV/MV substation serves a part of the MV network in the optimum way for that year. The corresponding investment and operating costs (including the cost of losses) are also calculated.

(c) In order to select the optimal sequence of configurations of the network for the total period of the study, dynamic programming techniques are applied, based on the previous set of selected network configurations for each year. The objective function of the problem includes the total capital cost, the O/M cost and the cost of losses. The output are the suggested investments and switching operations for each year (HV and MV lines, HV/MV substation constructions and their costs as well as the MV network configurations) and extreme voltage drop values and service quality indices. The total cost of other solutions, except for the optimal, as well as many other information can be obtained. As a result is the best solution for the particular arrangement of HV/MV substations.

(d) The above described steps (a), (b) and (c) are repeated, for different number of new HV/MV substations, and in each case a new solution for the total period is obtained. The final optimum solution is selected the one with the minimum cost.

4. STUDY CASE

The above described methodology has been applied to a region of Peloponnese, in Greece. This region is nowadays fed by a medium voltage 20kV feeder, that starts from a HV/MV substation. The main line of the feeder has a total length of 45km and feeds loads of a total maximum demand of 7MVA, Fig.1.
The area under examination is 168,615,000m^2 and was divided into 7,494 pixels. The dimensions of each pixel used for the investigation were selected to be 150x150m so that one 500kW WT may be installed in each pixel. The required wind speed data, that is the annual mean wind speed for each pixel, was obtained from the application of a wind potential prediction software using as reference wind measurements carried out at two sites within the investigated area. A typical wind speed distribution and the power curves of a 500kW WT were considered.
In Fig.2 a classification of the 7,494 pixels according to their LEC - section 3.1(a) - is presented, giving an overview of the most favorable areas. Next, by the application of the software described in section 3.1(b) to (d), the limits of the existing MV network for the connection of WP are determined. As an example, in Table 1, some of the results of the analysis are shown, indicating the WP that can be connected without violation of the constraints. For the connection of wind power higher than 5MW, the construction of a dedicated MV line is required, departing from the HV/MV substations, or an extension of the HV network. Consequently it can be concluded that the maximum RES power that can be connected to the existing MV feeder is about 5MW, dispersed or concentrated in one or more WPs.

For higher wind power penetration, a multiyear planning of the network is necessary, which is the main subject of this paper. For this purpose the method described in section 3.2, was applied.

First, the scenarios of WP development must be selected. Using GIS facilities, it was found that there are 1041 pixels with a slope less than 30% and annual mean wind speed higher than 5m/sec, considered as the minimum requirements for WP development. Next, considering that WPs of installed power of 2.5-5-10-15-20 or 25MW can be developed, the algorithm selects neighboring pixels that form one of the above WPs, so that the maximum energy production is obtained. The results are shown in Table 2. After that, taking into account that larger WPs are preferable than smaller ones, a set of 14 WPs was selected, where their mean wind speed was higher than 7.5m/sec. The 14 WPs, representing a total wind power of 130MW, are shown in Fig 3. For these WPs, a priority list was created, using the produced wind energy per installed MW (GWh/MW), and the first six of them (in bold characters), totaling 67.5MW, Table 3, were selected for the 10-year period of the study. In Table 4, the forecasted development of the existing and new loads is also indicated.

Three cases of new HV/MV substations was considered: Construction of one, two or three new substations. The case of two new substations was found to be the optimum one. The main features of this solution are illustrated in Fig.4, where the division of the area in 7,494 pixels and the sites of WPs and new loads are also shown.

More specifically, in year 1, the 150kV network is extended up to the new substation Nº1, 2x40/50MVA: the 5MW WP is connected, by a dedicated 20kV line and the existing 20kV network is properly rearranged (the existing line is opened at about 20km from the old substation). In the next years, up to the 5th, the new WPs and the new loads are fed from the old and the new substation (Nº1), by the construction of the required 20kV lines and rearrangements of the 20 kV network, so that the yearly losses are minimized.

In year 5, a new substation, Nº2, 20/25MVA is constructed, between the old and the Nº1 new one (25km from the old substation and 15km from the Nº1), Fig.4, and the 20kV network is properly rearranged, serving the WPs and loads. Then, from 5th year to 10th, the new loads and WPs are connected to the existing three 150/20 substations by construction of the required new MV lines. It is remarkable that all WPs are connected to the Nº1 new substation, while the Nº2 restricted to serve the loads of its area.

5. CONCLUSIONS

A method is presented for the planning of distribution networks in areas where high wind or other RES penetration is expected. It utilizes the GIS facilities, which provide the required information concerning land use, RES potential and distribution network data and loads.

In a preliminary study, the optimum RES sites are determined and properly classified. Next, the short time optimum integration of the RES in the MV network and their impact on the service quality of the consumers, can be determined. This optimization is based on the minimization of the Levelised Energy Cost (e.g. GRD/kWh) of the RES.

Finally, the method is extended for the optimum planning of the HV and MV network of the area, over a multiyear period, using the GIS facilities for the selection of different RES development scenarios.

The effectiveness of the method and the developed software is proved by its application to a real study case, in a region of Greece where favorable wind conditions exist.

6. REFERENCES

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TABLE 1: WP connection to 20kV feeder					
WP size	Already installed power MW	Connection Line length (km)	LEC GRD/kWh	Voltage change (%Vn) Before WP connection min/max	After WP connection min/max
1MW	0.0	0.048	7.551	86.66/100.00	86.20/100.00
	1.0	0.131	7.564	86.20/100.00	86.03/100.00
	2.0	0.135	7.565	86.03/100.00	86.12/100.02
	3.0	0.168	7.569	86.12/100.02	86.38/101/20
	4.0	0.176	7.570	86.38/101/20	86.86/102.71
	5.0	0.299	7.589	86.86/102.71	87.56/104.55
	6.0	4.438	8.213	87.56/104.55	88.74/105.97
	7.0	35.354	12.872	88.74/105.97	88.75/105.99
2.5MW	0.0	0.048	7.545	86.66/100.00	86.05/100.00
	2.5	0.436	7.570	86.05/100.00	86.86/102.15
	5.0	3.75	7.776	86.86/102.15	89.00/105.55
	7.5	30.371	9.373	89.00/105.55	89.23/105.86
5MW	0.0	2.253	7.610	86.66/100.00	86.86/101.66
	5.0	17.819	8.079	86.86/101.66	89.79/105/79

TABLE 2: Wind Park classification according to their power and mean wind speed. (1041 pixels with $\overline{V}_W$ >5m/sec and surface slop < 30^0)						
WP power (MW)	$\overline{V}_W$ (m/sec) 5-6	6-7	7-8	8-9	>9	Total
25	0	2	1	1	0	4
20	2	3	2	0	0	7
15	2	5	1	4	0	12
10	3	6	3	3	2	17
5	9	15	4	7	5	40
2.5	25	29	13	17	10	94

TABLE 3: Classification and priority list of the selected 14 wind parks.					
WP power (MW)	Selected Nº of WP (referred to the Table 2 number coding)	Energy produced GWh/year	mean wind speed (m/sec)	Energy produced per MW installed (GWh/MW)	Priority
25	1	95.2	8.10	3.81	**6**
	2	90.6	7.92	3.62	12
20	-	-	-	-	-
15	2	58.8	8.64	3.92	**4**
	1	57.3	8.90	8.82	**5**
10	6	37.0	7.97	3.70	9
	7	35.7	7.47	3.57	13
5	1	20.1	11.22	4.02	**2**
	4	20.25	9.17	4.05	**1**
	13	18.8	7.93	3.76	8
	15	18.9	7.84	3.78	7
2.5	14	10.0	8.73	4.00	**3**
	25	9.1	8.15	3.64	10
	32	9.1	7.55	3.64	11
	30	8.9	7.74	3.56	14

TABLE 4: Wind power and load development in area										
	Years									
Loads and WP	1	2	3	4	5	6	7	8	9	10
WP(MW)	5	5	2.5	-	15	-	15	-	25	-
WP(GWh/MW)	4.05	4.02	4.0	-	3.92	-	3.82	-	3.81	-
Old loads(MVA)	7	7.35	7.72	8.10	8.51	8.93	9.38	9.85	10.34	10.86
New loads (MVA)	-	-	0.4	-	0.4	-	0.4	-	0.4	-

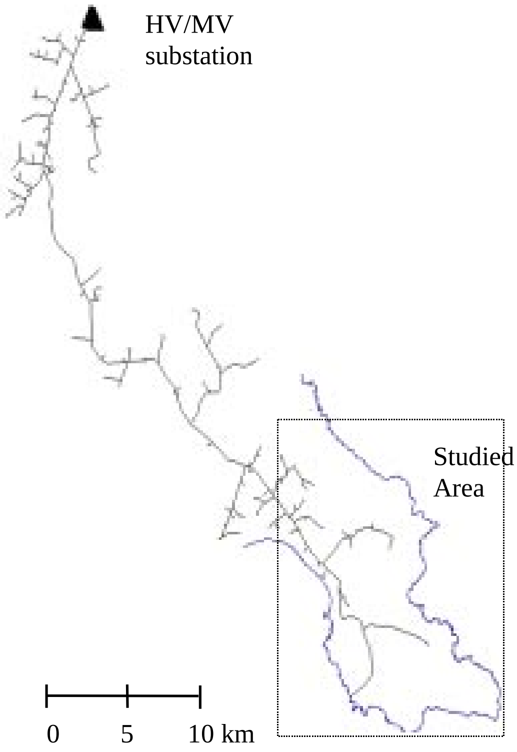

Figure 1: Existing 20 kV network:
- main line length of about 45km
- Total load maximum demand of about 7 MVA

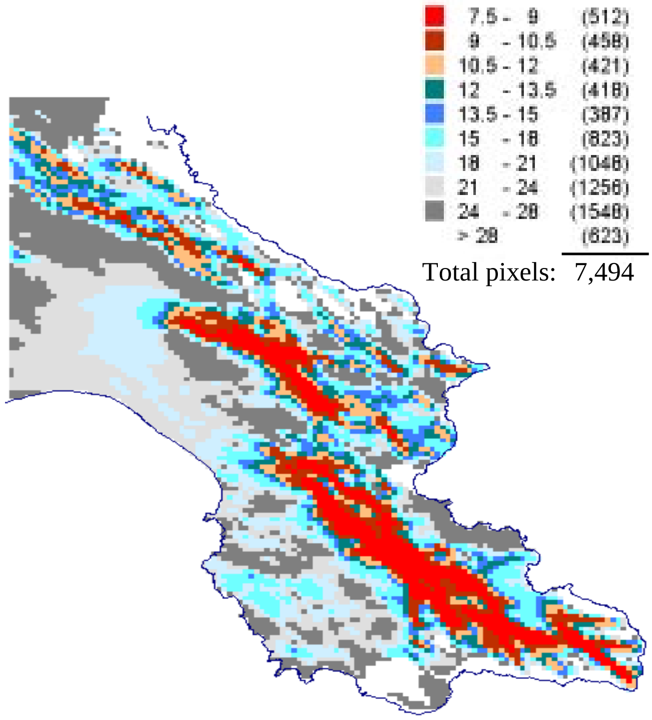

Figure 2: Classification of the pixels according to the production cost (GRD/kWh), if a 500kW WT is installed.

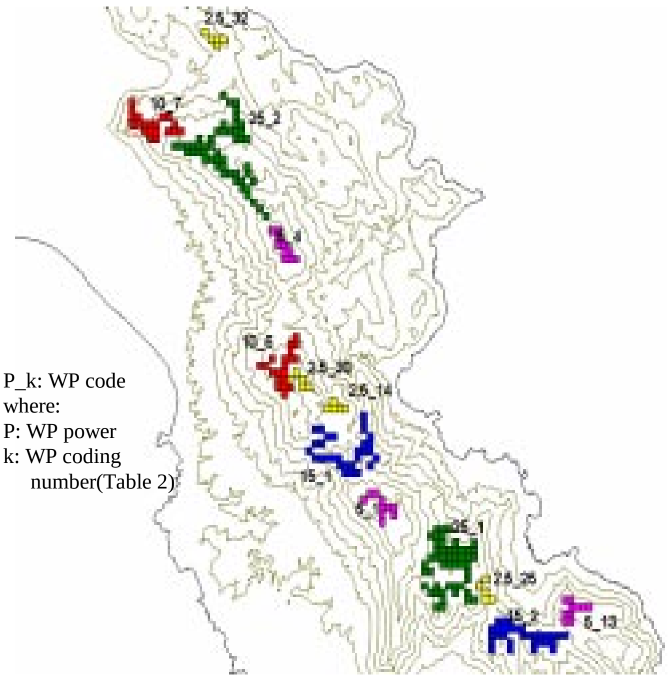

Figure 3: The 14 selected WP (130MW total).

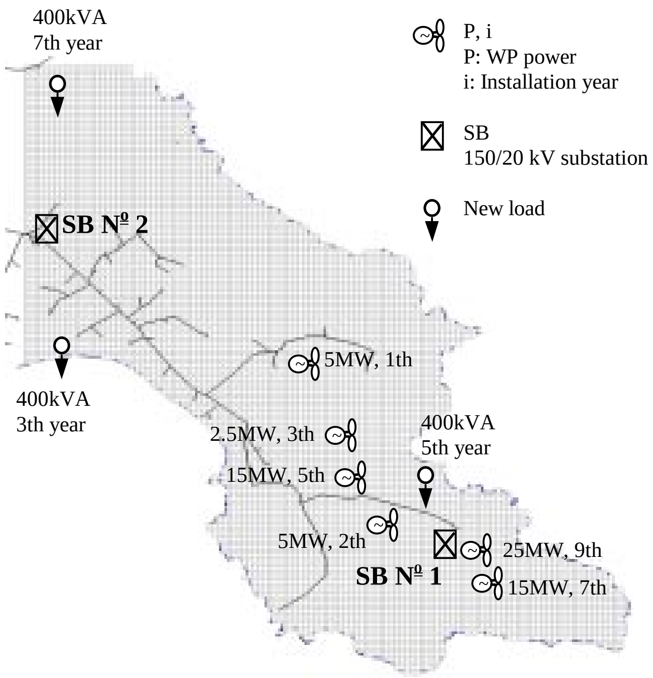

Figure 4: The MV network, new loads and the six WP of examined area.