A GIS-based design of power line and post-construction optimization

KOSTAS KAOUISIAS*, STELIOS ZONTOS**, EMMANUEL THALASSINAKIS*, ISIDOROS VITELLAS*

*Hellenic Distribution Network Operator, Islands Network Operation Department, Athens, GREECE
**EXERGIA S.A. Energy and Environment Consultants, Athens, GREECE
k.kausias@deddie.gr, s.zontos@exergia.gr, e.thalassinakis@deddie.gr, i.vitellas@deddie.gr

Abstract: - The context of the research reported in this paper is the design and construction of an Overhead Transmission Line with a specific focus in the analysis and efficiency optimization due to localized high intensity winds. The methodology described herein was applied to an HV Transmission Line in the island of Crete, Greece, which connects Ierapetra city and the power plant of Atherinolakkos on the remote south-east coast of Crete. Frequent interruption faults and subsequent outages in the electrical supply made it imperative to reconsider the design of the power line and apply optimized solutions from a holistic point of view by means of Geographic Information Systems, in-situ evaluation, and economic implication. This is inter alia a consequence of the design principles that the Greek Public Power Corporation has adopted and emphasizes the importance of optimal placement of towers, protective devices, reliability indices and environmental sustainability. These imperatives are underscored by the construction of Atherinolakkos power plant in order to take over some of the power generation burdens from other older thermal plants elsewhere on the island. Measures taken to tackle the problem that caused the faults are discussed in this paper. Tower and conductor selection, composite insulators, pendulum customization, uses and applications of GIS interlinks with Dispatch Centers are also presented and discussed in this paper.

Key-Words: - Overhead Transmission Lines, Geographic Information Systems, gust, reliability, faults, lightning, monitoring, optimization, isolated systems, island, high intensity wind

1 Introduction

The purpose of the electric transmission system is the interconnection of the electric energy producing power plants or generating stations with the loads. The system contains loops that assure that each load substation is supplied by at least two lines increasing its reliability.

Transmission systems must meet performance standards and criteria that ensure an acceptable level of quality of electric service, which means continuity of supply and constancy of voltage waveform and power system frequency. Reliability criteria for transmission systems must address both local interruptions of power supply at points in the network as well as widespread interruptions affecting population centers or entire regions.

However, when it comes to autonomous, isolated power systems this is not the case as outages and frequency anomalies may not be rare with direct or indirect impacts to the consumers or domestic electric equipment and even the normal operation of other RES plants. This leaves continuity of power supply as the main criterion for acceptable transmission system performance.

Isolated power systems, like those operating in large islands, face increased problems related to their operation and control. In most of these systems, the cost of electricity production is much higher than in interconnected systems due to the high operating costs of their thermal generating units. Renewable energy sources (RES) can often be used as a primary source of energy in such systems, as they are usually present in geographically remote areas. Though, an isolated power system with increased RES penetration has significant differences from an interconnected power system presenting low minimum to maximum demand ratio and significantly larger frequency deviations. Furthermore, quite often the installed thermal units have significant values of technical minimum that introduce problems in co-operation between thermal units and wind power making the operators disconnect some of the wind power production in order to avoid technical limits violations.

2 General background

Crete is the biggest island of Greece with a population of about 600,000. The power system of the island of Crete constitutes the largest autonomous sub-system of Greece with a considerable penetration of RES mainly in the form of wind farms (Fig.1). The topography of the island is mountainous and receives an abundance of...
sunshine, which justifies the interest in investing in renewable technologies. Most of the modern wind turbines are located in the eastern part of the island within Lassithi prefecture administration limits.

For covering the demand of the island of Crete, there are three thermal power plants, namely Linoperamata power plant (located at the center of the island, at the premises of Heraklion city), Chania power plant (located at the western part of the island) and Atherinolakkos power plant (located at the eastern lower part of the island). The overall installed capacity of these three power plants amounts for 817 MW [1]. The Atherinolakkos PP, burning heavy fuel oil with low sulphur, minimizes the environmental impact and operates in the most cost effective manner. Another crucial issue with the Atherinolakkos PP is its capacity to burn natural gas taking over some of the power generation burdens from other older Public Power Corporation plants elsewhere on the island.

2.1 The need for the implementation of the OTL Atherinolakkos – Grid

According to the 5-year and 10-year network development plan, conducted by the Hellenic TSO for islands, it was imperative the need for the expansion of the high voltage electric network in Crete. This imperative is underscored by several initiatives, briefly presented here, in order to:
- Improve electric system reliability locally and regionally
- Deliver economic savings for PPC per se and consumers
- Expand infrastructure to support national policy for penetration of RES

Construction work at the Atherinolakkos site, including support infrastructure began in January 2001. On this ground, a new high voltage overhead transmission line was designed, namely Atherinolakkos – Grid with power capacity 404 MVA. The power line had been completed just before the completion of the PP, that is mid 2004. Due to the future enhancement of the capacity of Atherinolakkos PP, it was provisioned the construction of Atherinolakkos – Grid II power line with a power capacity of 2x202MVA.

During January 2012, the peak demand in Crete was 631 MW and the annual wind energy penetration was around 18.7% [1]. The instantaneous wind power penetration reached 40% during some valley hours in winter and early spring. The installed RES power capacity of the island, mainly wind parks and a negligible photovoltaic installed capacity, at the beginning of 2012 was 232.9 MW a decent portion of which (more than 50%) are located at the Sitia region, Lassithi prefecture, on the eastern part of the island.

3 Transmission project design of the Atherinolakkos – Grid power line

3.1 Transmission design methodology

Environmental and safety issues are a top priority for PPC during the design of transmission power lines. Current legislation, best practices and environmental concerns call for the power lines to be designed, apart from the safety criteria and technical-economic factors, in a way that minimizes potential social impacts, while preserving landscapes and reduce negative effects to wildlife as much as possible. For these reasons the siting of the power line was done in such a way so as to avoid or minimize nuisance and, therefore, the reaction of the public and of the competent bodies (Ministries, prefecture bodies, etc).

The following criteria were considered in evaluation and consolidation of the power line route: (i) environmental, (ii) social, (iii) technical, and (iv) economic criteria. Each of these were further analyzed and visualized in corresponding maps according to at least criterion, as detailed below.
- Environmental criteria: Wildlife incl. flora, fauna, vegetation clearing, Protected areas, Environmental sensitive areas not officially recognized as protected ones, potential rivers or streams, etc.
- Social criteria: Population density, Cultural heritage, Land acquisition and tenure of land, tourism and recreation sites, proximity to coastal areas, distance and visibility from populated areas, etc.
- Technical criteria: Geology, Crossing with other infrastructure such as telecommunication or roads, River crossings, Hill shade, slopes and landscape profile, tension-sag and tension-strain curves, right-of-way, clearances, etc.
– Economic criteria: Cost per km (for the conductors) and cost per tonne times the number of towers.

More spatial constraints can be applied in order to exclude (or include) from the analysis unsuitable (or respectively suitable) areas as assessed by future planning of cities or other factors.

For the first time, an integrated GIS model was used by PPC for the design of a power line as part of the Greek grid providing the opportunity to automate time-consuming processes and optimize the output in terms of quality, documentation, visualization and time. With pure GIS software and GIS-oriented tools (PLS-CADD), PPC engineers could model routes and determine rights-of-way according to national, international standards and best practices. Fig 2 shows a typical example the modeling and visualization of a potential routing.

The model developed by the authors allowed for readily identification of suitable land corridors based on the constraints that the user each time imposed. These corridors were the derivation of a weighted-based calculation of the heterogeneous criteria as detailed above. The procedure was performed by a methodology that has been programmed in the GIS environment using inherent available tools (a graphical interface named model builder and Visual Basic programming).

A 0-10 scale was used by assigning high values to those layers dealing with natural aspects and indicating areas that the power lines must avoid, mid values to those data that should be avoided and low values to all other layers indicating the relatively small impact they have in the decision-making process.

3.3 Tower selection and conductor design

The design of a transmission line depends to a large extent on wind and ice loads that may be imposed on the conductor, overhead ground wire and supporting structure. These loadings are related generally to the geographical location of the line. After evaluation of climatic conditions, previous line operation experience and the importance of the line to the system, a heavy-constructed series steel lattice towers were used for supporting the two three-phase circuits and the Grosbeak ACSR conductor. As depicted in Fig. 3 and according to the standardization of PPC, the S4 heavy-double circuit tower type is designed for straight line (up to 6° running angle), the R4 type is designed for small angles (up to 10° running angle) and the T4 type is appropriate for up to 45° running angle; finally, terminal dead end towers that support conductors with up to 75° running angle are denoted as Z4.

Aluminum steel reinforced conductors (GROSBEAK 636000CM ACSR) were used, which are typical overhead electrical 150 kV conductors for the Greek power system. The characteristics of the specific conductor and its wires met the requirements of relevant IEC Standards.

A conservative approach was made mainly due to the importance of the specific power line as explained above. The loading and load factors were determined based on a 0+9” notion, meaning that the expected radial ice thickness equaled to 0 and the expected wind loading equaled to 9 psf (pounds per square foot). Despite the choice of 0+9”, some straight towers with small angle line (<6°) were upgraded to R4 type to improve the electrogeometric model of the power line.

4 Power line performance after construction

4.1 Post-construction behavior of the power line

After its construction the power line was subject to high intensity winds and lightnings. These phenomena caused an increased number of faults
especially during the first three years of operation to a total number of 72 towers. As can be seen in Table 1, from 2005 to 2007, the number of faults in the specific line as a percentage to the total number was in unacceptable high levels. In general, a grid fault (e.g. short-circuit, equipment breakdown, etc.) may be temporary or permanent. A temporary fault is cleared after re-energizing of a faulty grid branch. A permanent fault will persist until repaired by human intervention [2].

Table 1: Number of faults through the years

<table>
<thead>
<tr>
<th>Year</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of faults in the sub-system</td>
<td>8</td>
<td>12</td>
<td>14</td>
<td>13</td>
<td>9</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>Number of faults in the specific power line</td>
<td>0</td>
<td>6</td>
<td>8</td>
<td>7</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>of which, the number of permanent</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>of which, the number of temporary</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Percent of faults in the specific power line</td>
<td>0%</td>
<td>50%</td>
<td>57%</td>
<td>54%</td>
<td>33%</td>
<td>15%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Fig 4 shows the Load-Frequency diagram (on the left) on 26 December 2006 versus time. On the right, the same information is displayed but this time between 10:00 and 11:00 pm. The implications of these faults in the overall stability of the grid and the impact on the wind parks of the area is shown in Fig. 5, which is clear that due to these abnormal situations (faults), some RES installations have been off grid for a decent working time.

![Fig. 4 Load-frequency diagram on the power line](image)

![Fig. 5 Due to faults and instability factor, some wind parks have been off the grid](image)

4.2 Methodology to overcome the occurrence of faults

Before the existing structure or line became ready to be improved, a thorough records search was made, detailed field information obtained with comprehensive engineering calculations. A qualitative-quantitative mix approach and enrich of data was conducted. A first step was to identify the critical points of the power line and identify some kind of correlation with regard to location, weather effects, faults due to equipment mistakes, etc. An in-depth review of the design parameters and construction methods used for the existing transmission line was imperative. The purpose of such a thorough study was to clearly define the starting point and configuration before any expensive and/or time-consuming modification is made. Several essential questions were answered such as the basic design criteria, the specific overload factors, whether the line meet certain ice or wind criteria, the type of insulators and other hardware installations, etc. A survey was imperative to spot check clearances, span lengths, heights and elevations, etc.

The data acquired from this procedure was analyzed to determine the optimal plan for improvement. It should be kept in mind that any potential changes ought to comply with PPC Regulations and IEC Standards.

4.3 Measures taken for tackling the problem

Improving grounding on a transmission line normally decreases the number of outages on a shielded line. For this reason, the founding of the towers was made from reinforced concrete. Furthermore, the part of the tower that was intended to conduct and disperse the lightning current into the earth was designed as a foundation earth electrode arrangement. Special focus was given to the important criteria (shape and dimensions of the earth termination system and not the ground resistance value per se) when dealing with the dispersion of the lightning current whilst minimizing any potentially dangerous overvoltages.

In order to keep the ground resistance as low as possible and given the fact that at of the towers this value was as high as 20 Ohm, additional electrodes were installed in a straight line with an overall length of approx. 200 m per tower. Complementary to the above, in the case that the distance of a tower with the closest substation was less than 2 km and with a measured ground resistivity more than 10 Ohm, an extra earthing grid was installed with an overall length of 2 km. In doing so, the nearest seven towers to the substation were connected with a common conductor in order to minimize the possibility of faults due to lighting phenomena. This practice was in accordance with international standards and best practices in similar cases and in line with the PPC Guides [4-5].

For the improvement of the oscillation due to intensity winds performance tie-down weights were installed due to the substitution of conventional cap
and pin insulator strings with Sediver composite insulators [3]. Tie-down weights are used to control conductor position by preventing excessive uplift and swinging.

Conventional insulators used on transmission are standardized porcelain insulators with successful track record, useful lives, and strings that are heavy. On the other hand, composite insulators provide a number of advantages over the conventional ones such as a more propitious behavior to contamination effects and size reduction of the strings. The selection procedure of the proper size for the composite insulators included the consideration of all the important parameters of the power line, namely basic insulation level (BIL) determined by the minimum arching distance, switching surge with regard to clearances, frequency range, altitude, and level of contamination. Custom-shaped pendulums were also installed to lessen the swing angle of the conductors.

Another measure used to eliminate faults dealt with the free movement of the attachment points (insulators) in S4, R4 and T4 tower types and subsequent movement of either the insulator (for S4 and R4) or the connecting conductor (for T4) used in cases of large running angles. Each line section is terminated at each end by a strain structure that allows no longitudinal movement of the conductor attachment points as shown in Figure 6. The insulator strings in T4 and Z4 structures experience the full tension of the conductor and the conductor attached is not free to move in the direction of the line. A connecting conductor is attached for this reason. On the other hand, in S4 and R4 towers the insulators are free to move both transversely and longitudinally to the line. Any modest difference in conductor tension by means of natural or human-made phenomena between adjacent spans would result in a movement of the bottom of the insulator string and an equalization of the tensions between the spans. Given the free movement of the conductors in both cases, a different approach was made to tackle with potential short-circuit faults. In some S4 and R4 towers, in order to improve the electrogeometrical model, suspension structure supports were substituted with such structure allowing only free longitudinal movement (V-strings) but restrict movement transversely to the line. In T4 towers, two vertical insulators with RTV coating hanging from two distinct points of the tower body were used to minimize the free movement of the conductor in large running angles.

The overall design of the improved power line was made according to the 0+16” notion, meaning that the expected radial ice thickness equalled to 0 and the expected wind loading equaled to 16 psf. This was the first time in the Greek power system that such design specifications were applied partly because of the unexpected wind forces, but mainly due to the significance of the power line per se. After the abovementioned interventions, the power line has not given as much faults as before. The number of faults is below the average number of a typical power line in the interconnected power grid and independent to a large degree from intensive wind phenomena.

5 Proposed methods for optimized monitoring with regard to the operation conditions

Much analysis is done by the engineers responsible for the design to determine the maximum reliable capacity of each line (ordinarily less than its physical or thermal limit) to ensure spare capacity is available, should there be any failure in another part of the network. An even more comprehensive approach should be considered in isolated grid due to its inherent vulnerabilities. The objective is to have the continuing availability of energy services, at the lowest cost consistent with sustainable criteria.

For the Dispatching Center of Crete it is not feasible yet to foresee the temperature distribution or sag along the conductor route; thus, the monitoring and control of current load is not feasible to be tracked in a real-time and on-line mode. The maximum applicable current load is set as a compromise between the operation conditions, history records and risk minimization. Typically, worst case weather conditions are assumed but clearly this has a significant trade-off in terms of ampacity.

It is clear that lack of detail weather data may be detrimental. Weather has an effect on the system because of changes in energy demand based on
temperature and outages. Suggested methods for monitor and control from the dispatching center include: (i) weather-based models (ii) temperature-based models (iii) tension-based models.

The design capacity of a transmission line is calculated by making deterministic assumptions about the ambient temperature, wind speed and other weather related variables. The design operating temperature is that when the sag is more than that required to meet the statutory ground clearance under these design assumptions. Some of the variables that affect the conductor sag include weather conditions, cross section of the conductor and its manufacturer’s specifications. To withstand these effects the line is usually designed with design safety margins and can operate reliably and safely as long as the line sag does not violate the design limits [6].

The data can be utilized for engineering studies and also for system planning purpose, such as clearance warning and real-time load flow decisions. When the sag of a line is approaching the statutory clearance limits, the system provides the operator with a warning in order to operate in the maximum allowable safe load. Furthermore, the benefit of having access to continuous real time rating gives the operator better tools to predict the ampacity and load factor for different times of the day in the most critical points. Transmission of data originated from sensors as detailed above into a GIS to be displayed to the control room of the dispatching center is significant (Fig. 7). The GIS platform will be responsible for further processing of the emergency event record, which includes:

− pre-processing of the received information and representation of the information on a geographic map;
− determining coordinates of the emergency event;
− analyzing data of the event;
− recording the information about the event in the dispatcher’s database;
− generating the information record of the event;
− supervising the route based on the GPS.

6 Conclusion
A GIS-based application has been developed for transmission line siting. This model supports from the planning phase to the engineering design phase and provides solution for the siting process and environmental mandates according to national legislative framework. GIS technology has strong adaptability to the routing of a power line and the siting of towers as it offers a plethora of merits.

It is important to optimize the process of designing the route the transmission line will follow by maximizing utilization of available data by means of GIS technology; however, there are times that this may be inefficient and a more conservative approach should be followed along with use of engineer’s experience. Clearly, data quantity and quality is of significant importance as these are the baseline that the design will build on. At the same time proper attention should be given to minimization of costs and environmental concerns as these parameters may impose negative impact to future upgrade of a power line. A next step is to integrate this model with other GIS-based software used in PPC and constitutes the repository for all plant and lines information. This, along with the enhancement of the Dispatching Center with contemporary monitoring and control methods will allow for a more automated, safe and efficient process of using the power system as a whole.

References:
[1] www.dei.gr