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WiND FoRECASTING SERVICE
USING ADAPTIVE NON-LINEAR KALMAN FILTERS

PROJECT GOALS AND OBJECTIVES – EXPECTED RESULTS

Motivation

Over the last 100 years, the amount of carbon dioxide (CO_2) in the atmosphere has been rapidly increased increasing the earth average temperature and leading to **climate change**. It is expected that natural disasters related to the climate change will continue to cause tremendous damages unless the global community modifies the way of production and usage of energy. In response to this threat, the ***U**nited **N**ations **F**ramework **C**onvention on **C**limate **C**hange* proposed the Kyoto Protocol in order to fight global warming. Under this protocol 37 countries (“Annex I Countries), including Greece, commit themselves to a reduction of four greenhouse gases (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride) and two groups of gases (hydrofluorocarbons and perfluorocarbons) produced by them. However a significant percent of CO_2 is emitting in the atmosphere while producing energy with traditional procedures, paving the way for a “clean” generation of energy. **Renewable energy** is energy which comes from natural resources. Renewable energy is growing strongly supplying an estimated of 16% of global final energy consumption. **Wind power**, as an alternative to fossil fuels, is renewable, clean and produces no greenhouse gas emissions during its operation. At the end of 2010, worldwide capacity of wind energy parks was 197 gigawatts (Gws).

As the penetration of electricity generated by wind farms in the electrical grids is increasing, reliable wind power prediction has shown to be a crucial procedure in electrical utilities operation. Predictions can be used, for example, in order to create an optimal combination of wind power production with other power sources. Moreover short-term wind forecasts have great value in optimizing the operation of wind energy parks. For example strong wind gusts can be predicted securing the wind turbines by turning on the brake system for each wind turbine. On the other hand, time periods with low speed of wind can be predicted allowing wind park operators to proceed to routine maintenance without loosing energy production.

Concepts – Scientific Objectives

The main concept of this project is to develop a real-time, recursive and non-linear technological framework for accurate short and long term wind forecast that are derived from numerical and physical weather prediction models. The proposed model extends the traditional non-linear Kalman filters (Extended Kalman Filters) towards a direction that allows real-time forecasting and recursive estimation of the unknown non-linear function of spatial-temporal distribution of wind flow over complex terrain. Therefore, the traditional Kalman filters are enhanced with adaptive algorithms leading to accurate estimations of the unknown covariance of the measurements by continuously train the non-linear Kalman filter with up-to-date measurements under a real-time computational framework. In this project, we investigate solutions that incorporate a recursive non-linear model into the framework of Extended Kalman filters, resulting into a new smart, adaptive, non-linear prediction solution, capable of real-time estimating the unknown non-linear wind power model.

In addition, we inter-weave a Service Oriented Architecture (SOA) in order to communicate, in real time, with the SCADA wind turbines and retrieve wind flow operational characteristics, associating all this information with the adaptive, recursive, non-linear filter

Expected Results

The following expected results are provided by the project:

1. An innovative hybrid (physical and statistical) wind forecasting scheme using a real -time, adaptive, non linear filtering procedure, which is suitable both for short and long term wind power prediction.

2. A service oriented architecture (SOA) for (i) retrieving either data coming from private anemometer sensors, and public available data on the Web, (ii) communicating with the SCADA system of the wind park (to retrieve information regarding the operation of the Wind turbines) and (iii) applying the proposed adaptive wind forecasting framework under a real-time computational approach.

3. The investigation of scenarios at different operational use cases, taking into account the different user/system requirements of extended region in which the wind park operates; these scenarios are used for evaluation of proposed forecasting scheme.

PROGRESS BEYOND THE STATE OF THE ART

As described above wind forecasting is a crucial procedure in wind energy production and can be divided in two major time scales: From milliseconds to seconds (first scale) in order to optimize the turbine control itself and from minutes to weeks (second scale) to optimize and balance the distribution of wind energy production in the electrical grid. Current wind forecasting systems are divided into two main groups:

- *Forecast models based on physical approach* which consists of several submodels that translate the Numerical Weather Prediction (NWP) at a certain grid point and model level, to wind power forecast at the location of the turbine and at turbine height.

- *Forecast models based on statistical approach* which consists of statistical models whose parameters are estimated from data in order to define the relation between meteorological predictions and wind forecast without taking into account any physical phenomena.

The physical models try to use physical considerations as long as possible to reach the best possible estimate of the local wind speed before using Model Output Statistics to reduce the remaining error. On the other hand, statistical models try to find the relationships between a wealth of explanatory variables including NWP results, and measured power data from wind park SCADA system, often using recursive techniques.

Physical models consists of three main steps; (i) ***downscaling***, (ii) ***conversion to power*** and (iii) ***upscaling***. The wind speed and direction from the relevant NWP level is scaled to the hub height of the turbine. The next step is the downscaling procedure. The physical approach uses a meso-scale or a microscale model for downscaling. This can be done in two ways: (a) the forecasting model is running every time the NWP model is run, while the NWP model is used for boundary conditions and initialization; (b) the meso-scale model is running for various cases in a look-up table approach. In demanding situations, like wind parks in very complex terrain with high heights of wind turbines, the NWP resolution is too coarse to resolve local flow patterns and additional physical considerations of the wind flow are needed. The downscaling procedure yields a wind speed and direction for each turbine hub height. This information is converted to power either using the manufacturer's ***power curve*** or estimating the power curve from the measured wind speed and direction and measured power from past measurements using an auto-regressive least square method. Measured (online) power data can be used as additional input in order to improve the residuals errors using a self-calibrating recursive model. This procedure can have the form of an explicit statistical model combined with auto-regressive statistical method or can have the form of an adaptive non linear Kalman filter. More sophisticated models use Artificial Neural Networks. The above procedure predicts the energy produced by a single wind park. Since energy utilities are interested in predicting the energy for the total area they service, the upscaling from the single results to the total area is the last step.

Landberg developed a short-term prediction model based on physical reasoning similar to the methodology described above. ***Marti Perez*** developed LocalPred and RegioPred, which involve adaptive optimization of the NWP input, time series modelling, mesoscale modelling with MM5 and power curve modelling. The ***Institute for Informatics and Mathematical Modelling*** of the ***Technical University of Denmark*** developed The Wind Power Prediction Tool (WPPT), using an adaptive recursive least square estimation for estimation from 0.5 up to 36 hours ahead. Prediction is based on a combination of on-line measurements of power production from selected wind farms, power measurements for all wind turbines in the area and numerical weather predictions of wind speed and wind direction. ***Armines and Ral*** have developed a short-term wind power forecasting system based on time series analysis to predict the output of wind farms in the framework of LEMNOS project. Various statistical approaches have been tested resulting in a final model selection using a fuzzy neural network. Moreover Armines (project ***MORE-CARE***) developed a 48/72 hours forecasting system based on both on-line SCADA data and NWPs. The ISET (Institute fur Solare Energieversorgungstechnik) developed a short-term forecasting system using the DWD model and neural networks.

In this project, we will extend the aforementioned methodologies by incorporating recursive non-linear autoregressive models (RNAR) in the area of adaptive non-linear Kalman filtering for wind forecasting. We will also implement a Web service interface able to retrieve information from different available sources (Web and the SCADA system of the Wind turbines) for wind forecasting. The web service will exploit SOA technologies resulting in a dramatic reduction of the total computational complexity.

TECHNICAL DESCRIPTION, SCIENTIFIC/TECHNOLOGICAL METHODOLOGY, OVERALL STRATEGY AND ASSOCIATED WORK PLAN

Overall Strategy and Technological Methodology

In this project, we adopt an iterative technological methodology in order to increase project effectiveness and simultaneously provide a consistent risk management plan. The proposed iterative research methodology is applied into two main research directions; (i) the intra WPs integration policy, where the results of each WP are benchmarked and validated in order to satisfy the particular WP objectives and (ii) the inter-WPs integration policy, in which the technology of each WP are integrated, while, in the sequel, the aggregate results are “fed back” to the technological WPs to update the respective WP technology. Figure 1 presents the proposed iterative technological methodology.

The requirements/ specification (WP1) are used as a guideline of the two technological WPs (WP2-3), which are integrated in the WP4 of this project. The integration results update the technologies of the WPs 1-2 as well as of the initial architecture described in WP1. A two phase iteration strategy is adopted, each of duration of one year. The structure of this project is decomposed into the following technological WPs.

Technical Description and Associated Work Plan

W.P.1 SYSTEM REQUIREMENTS

The main purpose of this WP is to define (i) the requirements of the wind forecasting service, (ii) to crystallize the system architecture and finally (iii) to shape up the scenarios, which are used for system assessment. In this context, we initial gather the end-user and system (SCADA structure, location of wind park, spatial distribution of wind turbines, etc) requirements. In the following, we identify the specifications of the proposed technology as well as the most suitable architecture applied for a wind forecasting service in order to increase the efficiency of the Wind Power. Finally, in this WP, we define the different scenarios over which the proposed technology will be validated towards a more efficient Wind Power architecture.

W.P.2 IMPLEMENTATION OF NUMERICAL WEATHER MODEL

In this WP a physical forecast system that takes the output from external numerical weather prediction (NWP) model will be developed. The NWP models are formulated from fundamental principles of physics theory (conservation of mass, momentum and energy, and the equation of state for the constituents of air) which yields a set of differential equations that are solved on a three-dimensional grid. In this project, we will use the **MM5 mesoscale model**. The MM5 is a limited-area, terrain following sigma-coordinate model designed to simulate and predict mesoscale and regional-scale atmospheric circulation. Terrestrial and isobaric meteorological data are horizontally interpolated from latitude-longitude grid to mesoscale rectangular domain. Since the interpolation of the meteorological data does not provide much mesoscale detail, the interpolated data can be enhanced with observations from the standard network of stations using a multiquadratic auto-regressive technique.

W.P.3 DESIGN AND DEVELOPMENT OF AN ADAPTIVE NON-LINEAR KALMAN FILTER FOR WIND POWER FORECASTING

In this WP, we develop an adaptive non-linear technological framework for wind power forecasting. Emphasis will be given in the implementation of a real-time wind forecast model, which is a crucial factor for a short-term prediction, a very useful process for controlling the Wind Turbines. The traditional linear approaches, like for example, the use of Kalman filters, fail to provide an efficient short term prediction. This is mainly due to the fact that high non-linearities appear in the models, which are actually a chaotic system, i.e., very small variation of the initial conditions can occur large scale variations of the model output.

The main difficulty in the wind forecasting is that the (a) the non-linear model is not known, let alone it is dynamically changed through time and (b) the training step is not a straightforward process requiring significant computational time to avoid local minima. In this project, we address these difficulties by investigating an adaptable (recursive) non-linear technological framework. The proposed technology assumes an initially trained non-linear model, simulated, for example, by an artificial neural network architecture, and then, through the application of the perturbation theory, dynamically adjusts the model parameters in a way that (a) the current conditions, as expressed by the error between the predicted and the actual measured value, is trusted as much as possible, with (b) a minimum degradation of the previous obtained knowledge is achieved. The main advanced of this methodology is that (i) recursively estimate the non-linear model parameters and (ii) it is of small computational complexity, which is a very important requirement for an efficient short – term wind forecasting. The whole structure resembles “Transfer Learning” methodologies applied in wind forecasting.

W.P.4 WIND-FORECAST WEB SERVICE IMPLEMENTATION

This WP integration the technological achievements of the aforementioned two WPs into a common framework able to efficient predict the wind characteristics, either for short-term or long – term use. A service oriented architecture (SOA) is adopted for the technology implementation. The architecture acquires the necessary parameters of the model forecast through the implementation of Web services that communicates either between private wind anemometers (the Infometrics has such types of sensors) or public weather forecast portals. In addition, the implemented Web service will interface with the SCADA systems that controls the wind park in order to have accurate past information regarding the characteristics and the spatio-temporal distribution of the wind flow and to retrieve current operational status of the wind turbines. SOA dramatically reduces the required time used to perform the prediction.

Integration is achieved under a three-phase iterative framework. Each integration phase will completed at the end of a project year. The results of the integration are reported and are used as feedback for updating either the technologies, achieved in WPs2,3, or the system architecture as provided by the WP1. This interwoven, iterative technological methodology is very suitable for an efficient implementation framework of this project.