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DISTRIBUTED MULTI-OBJECTIVE OPTIMAL CONTROL FOR WIND FARMS

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Abstract
The work is devoted to the development of an agent-based approach and decentralized control principle of the distributed objects and technological processes. The task is focused on the design and analysis the new criteria of optimization via Multi-Objective optimal control of energies balance, controlling the wind farm as a team of agents, and not like a single isolated system. To show the advantages was developed an interface in C++ showing the wind simulation, the behavior of the wind farm using the new distributed intelligent control system and the comparison with the centralized system.

Key words
Multi agent systems, Multi-objective optimization, Distributed energy recourses.

1 Introduction

Wind energy is the world's fastest growing energy source. The amount of electricity produced by wind turbines is growing rapidly in Europe, Asia, and the United States for both environmental and economic reasons. The total installed capacity of wind energy in the world has quadrupled since 1997. Wind has been the fastest growing energy source in the world since 1990, with an average annual growth rate of 25 percent [Daniels. Jhonson, 2004].

Wind farms are energy generation systems being autonomous and controllable generating units. At current technological status, each set turbine-generator-power converter should be considered as a unit. These units work as an individual system for variable speed systems. Variable speed wind systems demand for an appropriate control of operating point at different wind regimens as well they can operate at different rotational speed and, consequently, at different system efficiency. Control characteristics of each machine are based on associated power converter that implements control on power flow to the grid [Costa, Martins, Carvalho, 2005].

For this reason every wind turbine can be associated as an agent, an agent is an intelligent entity which can apperceive the environment, observe the state of the environment by sensor, and take some actions to change the state. The characters of agent are autonomy, reasoning, cooperation, learning by itself and so on. The Wind turbines are located on a wind farm so a Multi-Agent System (MAS) are the most similar approach to control the whole wind fam. Multi-Agent System is a computational system where several autonomous or semi-autonomous agents interact and cooperate or compete to perform some set of tasks or satisfy some set of goals.

Multi-agent technology is not yet widely applied in power control systems. However, it has a large potential for bottom-up distributed control of a network with large-scale and medium-scale renewable energy resources (RES), distributed energy recourses (DER) and flexible hybrid integration are the of future power systems. At least two major European R&D projects (Micro Grids [Oyarzabal et al. 2005] and CRISP [Ramphuis et al. 2006]) have investigated this potential [Schaeffer et al. 2006].

2 Obtaining Wind Power

A wind turbine obtains the power output by converting the force of the wind into torque acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.

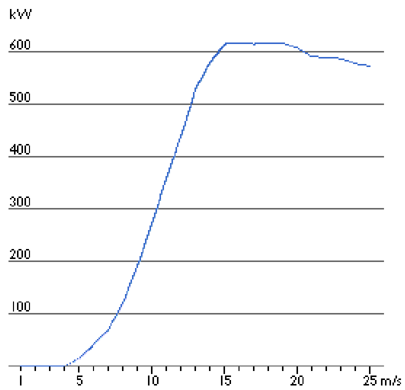

Figure 1. Power curve for a typical turbine 600 kW, form Danish Wind Industry Association.

Betz' law expression (1) says that you can only convert less than 16/27 (or 59%) of the kinetic energy in the wind to mechanical energy using a wind turbine, this law is expressed in the following expression [Danish Wind Industry Association, 2003],

$$P\max = \left(\frac{16}{27}\right)\left(\frac{\rho}{2}v^3\right)\left(\frac{D^2\pi}{4}\right) \qquad (1)$$

where is the density of the air in kg/m^3, v the velocity of the air in m/s, and D de diameter of the wind turbine.

The Figure 1 shows a power curve for a typical Danish 600 kW wind turbine. The output power of the turbine depends on the speed of the wind. At velocities above 5 m/s the power output is zero, and the output at velocities graters than 15 m/s the efficiency of the wind turbine decrease.

The wind turbine yaw mechanism is used to turn the wind turbine rotor against the wind. The wind turbine is said to have a yaw error (2), if the rotor is not perpendicular to the wind. A yaw error implies that a lower share of the energy in the wind will be running through the rotor area. (The share will drop to the cosine of the yaw error). Wind turbines which are running with a yaw error are therefore subject to larger fatigue loads than wind turbines which are yawed in a perpendicular direction against the wind. Almost all horizontal axis wind turbines use forced yawing, it means they use a mechanism which uses electric motors and gearboxes to keep the turbine yawed against the wind.

The yaw mechanism is activated by the electronic controller which several times per second checks the position of the wind vane on the turbine, whenever the turbine is running.

The measurement of wind speeds is usually done using a cup anemometer. The cup anemometer has a vertical axis and three cups which capture the wind. The number of revolutions per minute is registered electronically. Normally, the anemometer is fitted with a wind vane to detect the wind direction.

$$\phi(\mathrm{v}) = 300\left(\tanh\left(\frac{v\cos(\alpha-\theta)}{6}+2\right)+1\right) \qquad (2)$$

Where the yaw error is expressed using the difference between α and θ. α is the angle of the nacelle in relation to the horizontal axis and θ is the angle of the wind direction also in relation to the horizontal axis, the constants are from the figure 1.

Other effect to take in to account is the park effect. Since a wind turbine generates electricity from the energy in the wind, the wind leaving the turbine must have lower energy content than the wind arriving in front of the turbine. Wind turbines in parks are usually spaced at least three rotor diameters from one another in order to avoid too much turbulence around the turbines downstream. In the prevailing wind direction turbines are usually spaced even farther apart.

As a rule, turbines in wind parks are usually spaced somewhere between 5 and 9 rotor diameters apart in the prevailing wind direction, and between 3 and 5 diameters apart in the direction perpendicular to the prevailing winds [Danish Wind Industry Association, 2003].

3 Multi Agent System

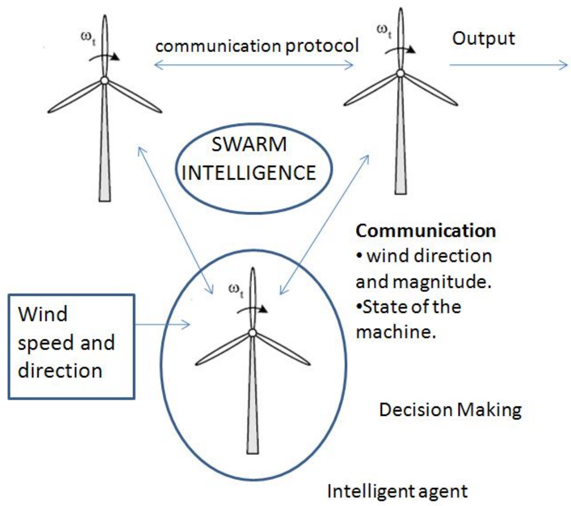

Figure 2 Brief description of the Multi Agent System

The Multi Agent System can be described by the figure 2; the main task of the Multi Agent System is to optimize the total power received from the wind balancing the gotten power and the power used to the reorientation of every turbine (correcting the yaw error).

The group of robots will be defined by $R_j=(j= 1,n)$. The actual state of every turbine will be defined by the vector $S_j(t)=<s_{1j}, s_{2j}, \ldots, s_{mn}>$ in this case the state of every agent will be the actual position of the angle respect to the horizontal axis $\alpha_j=(j= 1,n)$.

The state of the environment $E(t)=<e_1,e_2, \ldots, e_w>$ will be defined by the velocity vector sensed by the anemometer in magnitude $v_j=(j= 1,n)$ and direction $\theta_j=(j= 1,n)$.

Decision Variables

$$X = [S_1, S_2, \ldots, S_n]^T \qquad X \in \Omega$$

$$X = [\alpha_1, \alpha_2, \ldots, \alpha_n]^T \qquad X \in \Omega$$

Functions

$$F(x) = [f_1(x), f_2(x) \ldots f_k(x)]^T$$

$$f_1(x) = \sum_{i-0}^{n} P\max_i - \sum_{i=0}^{n} K\left(\tanh\left(\frac{v_i\cos(\alpha_i - \theta_i)}{6} - 2\right) + 1\right)$$

$$f_2(x) = \sum_{i-0}^{n} T\frac{(\alpha_i^{t-1} - \alpha_i)^2}{\Delta t^2} \qquad (3)$$

$$g(x) = \forall i \in \{1, \ldots, n\}, \left|\alpha_i^{t-1} - \alpha_i\right| - \pi/24 \le 0 \qquad (4)$$

A general Multi-Objective problem is defined as minimizing (or maximizing) $F(x) = (f_1(x),\ldots,f_k(x))$ subject to $g_i(x) \le 0$, $i = \{1,\ldots,m\}$, and $h_j(x) = 0$, $j = \{1,\ldots, p\}$ $x \in \Omega$. An MOP solution minimizes (or maximizes) the components of a vector F(x) where x is a n-dimensional decision variable vector $x = (x_1,\ldots, x_n)$ from some universe Ω. It is noted that $g_i(x) \le 0$ and $h_j(x) = 0$ represent constraints that must be fulfilled while minimizing (or maximizing) F(x) and Ω contains all possible x that can be used to satisfy an evaluation of F(x) [Coello, 2007].

To describe the targets functions, it is necessary to understand the objectives, one of them is to find the optimum balance between the energy sent to the grid by the wind farm, and the energy used to correct the yaw error in other word to reorient the nacelle and the blades of the turbine to obtain the maximum of energy(3) with machine response restrictions (4); the other one is to get the correct yaw angle to receive the maximum power form the wind before the flow current of the wind arrive to the corresponding turbine, it means using the information of the environment $E(t)=<e_1,e_2, \ldots, e_w>$ of the other agents, get the correct yaw angle before the wind flux arrive.

An other important objective is to be to design the yaw strategy which meets the requirements to keep the nacelle in wind direction and keep the yawing at a minimum avoiding the yawing in cases of local turbulence, the Multi Agent System makes it possible because the agents (turbines) uses a larger point of view of the correct direction of the wind, because every agent shares whit the other his state of the environment $E(t)=<e_1,e_2, \ldots, e_w>$.

To achieve those targets every agent of the team star the algorithm sending the information of the environment and e_w his current state s_1 to a common board, the next step is to read the board and use this information.

To avoid use unnecessary information (information of wind that already passed thought the current turbine) from the other agents is applied the criteria described in the expression (5).

$$\theta_j + \frac{\pi}{2} < \tan^{-1}\frac{y - y_j}{x - x_j} \ge \theta_j - \frac{\pi}{2} \qquad (5)$$

Where x, y are the position of the current agent x_j, y_j are the position of the other agent and θ_j the direction of the wind sensed by the other agent. The information that passes the criteria will be used in the future.

With the current data, the next step is to calculate the average angle of the farm in function of the power and the direction of the wind in every turbine and calculate the optimal angular velocity to reorient every turbine. In order to find the optimal solution of the Multi-Objective problem equations (3) and (4) of the reorientation have been used NSGAII algorithm. The NSGAII algorithm has been proposed by Deb et al. in 2001 [Deb et al. 2002]. The progress toward the Pareto set is here due to the Pareto ranking that divides the population into nondominated subsets: first, all nondominated individuals of the population are labeled as being of rank 1; then they are temporarily removed from the population and the process is repeated: the nondominated individuals of the remainder of the population are given rank 2, and so on, until the whole population is ranked. The diversity preserving technique is based on the crowding distance one of the possible estimations of the density of the solutions belonging to the same non dominated subset. NSGAII selection is based on tournaments i.e. to choose an individual for reproduction; T individuals are randomly picked from the population and compared to each other using the comparison operator defined above. The winner then becomes a genitor. NSGAII replacement is deterministic: it consists in merging all parents and offspring, and choosing the N best individuals in that global population using the same comparison operator.

For all test problems at different wind speeds with NSGAII, was used a population of size 100, a crossover probability of 0.8, a mutation probability of $1/n$, (where n, is the number of variables).Was run NSGA-II for 150 generations. The variables are treated as real numbers and the simulated binary crossover (SBX) [Deb, 2001] and the real-parameter mutation operator [Deb, Agrawal, 1995] was used.

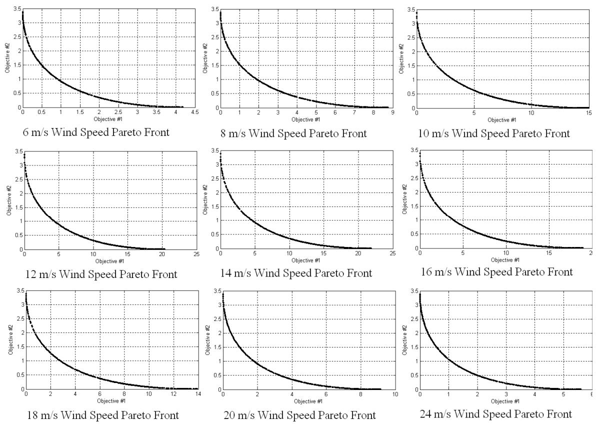

Figure 3 Pareto fronts gotten using NSGA-II multi-objective genetic algorithm. The yaw error is 30 degrees and the scales are in kw.

Using the data of the multi-objective Pareto fronts obtained in the figure 3 it's possible to perform an interpolation and get the angular velocity optimal strategy (figure 4) taking in to account the priority of the reorientation and the behavior of the environment.

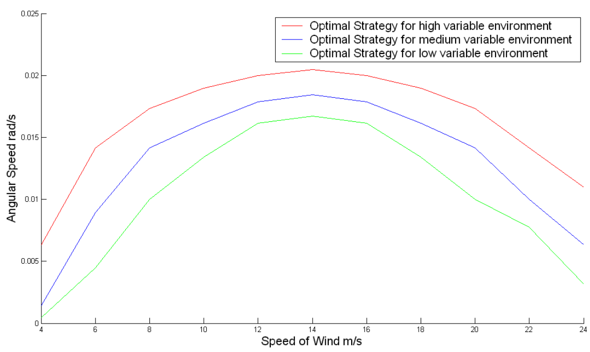

Figure 4 Optimal strategies Speed of the wind vs angular speed of reorientation

The last step is to set the optimum yaw angle in the current turbine with the optimal angular speed.

4 Simulation of the Wind Farm

The modeling of wind speed modeling is very important because it dictates the performances of wind generators and determines the features offered by a simulator for prediction of the energy output and analysis of the energy conversion and system dynamics.

The design of the wind simulator is based in the parameters of the wind farm showed in the first chapter and was developed in C++ Borland Builder.

In the figure 5 is shown the simulation of the whole wind farm the white dots are wind turbines, the black arrows are the blades and the other arrows are the flow of the wind showing the velocity using a color scale and the direction using the arrows.

The platform changes the direction of the wind every $\pi/6$ of the 2π of the horizon, and between 5 to 20 m/s the speed, also is a variable the duration of the wind on this direction and magnitude.

As shown in the figure 5 the platform also has 3 graphs of comparison between two models, the first one describe how actually work a wind farm correcting the yaw error just

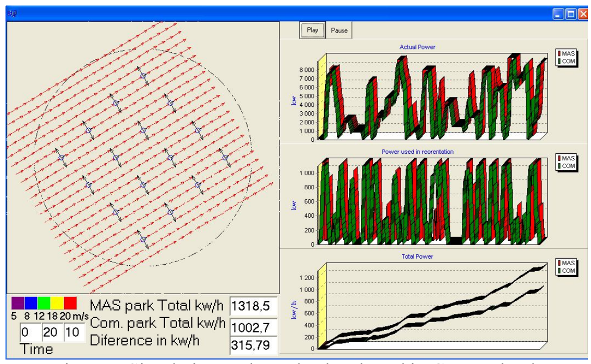

Figure 5 Simulation and graphs developed in C++Borland

when the turbines feel the changes of the wind, and the Multi Agent System for optimal balance of energy. In the fist graph is shown the actual power got by the whole wind farm, the second one shows the actual power used to reorient every turbine to the right direction (correct the yaw error), and the third graph describes the global sum of the gotten power minus the power used to the reorientation.

5 Experimental Results

To analyze the results it is necessary to evaluate every objective in the design of the Multi Agent System.

One of the main objectives to be achieved was to get the correct orientation (correct the yaw error) using the data obtained by other agents, in the figure 6 we can appreciate how after change the direction of the wind the agent in the top starts the reorientation (correct the yaw error) even when he don't sense the new direction of the wind.

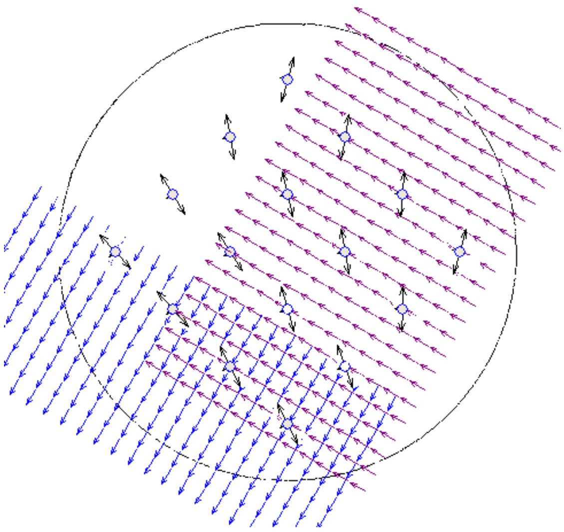

Figure 6 Simulation developed in C++Borland

The other objective was to get the maximum energy from the wind finding the optimal balance of energy between the energy sent to the grid by the wind farm, and the energy used to correct the yaw error. To analyze this objective need to be plotted those powers and to obtain a point of comparison, the graph also show how work a common yaw control. To obtain the graph is used the expressions (6) and (7). In the first graph of the figure 7 is appreciable the larger amount of energy gotten by the Multi Agent System, but in the second graph is appreciable how the MAS used more energy at the start than the common control, it means that was better to correct the yaw error as fast as possible to get the maximum energy in this situation, and in the last graph is shown the total energy in kW/h of the both controls, is appreciable the advantage of the MAS.

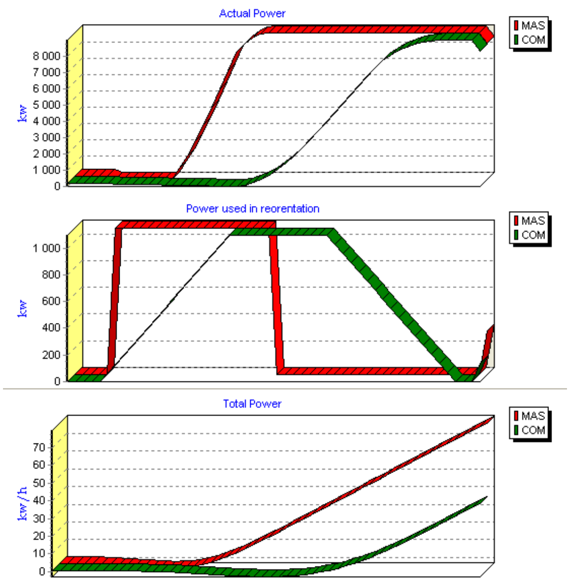

Figure 7 Comparison between powers MAS and Typical controls

$$Pp = \sum_{j=0}^{n} 300\left(\tanh\left(\tfrac{v_j \cos(\alpha_j - \theta_j)}{6} - 2\right) + 1\right) \quad (6)$$

$$Pa = \sum_{j=0}^{n} T \frac{\Delta \beta_j^{\,2}}{\Delta t^2} \quad (7)$$

To compare globally the behavior of the MAS and the commonly used control system, is analyzed the figure 8, this graph shows the recompilation of energy in kW/h in a equivalent of 20 minutes (1200 cycles) in a high variable environment, the results are 1318 kW/h MAS park, and 102 kW/h common control the difference between those powers is 315 kW/h it means that the MAS control is a 20% more efficient than the standard control. The actual wind farm has 16 turbines the efficiency of the MAS control gives the result like another 3 turbines had been working in the farm.

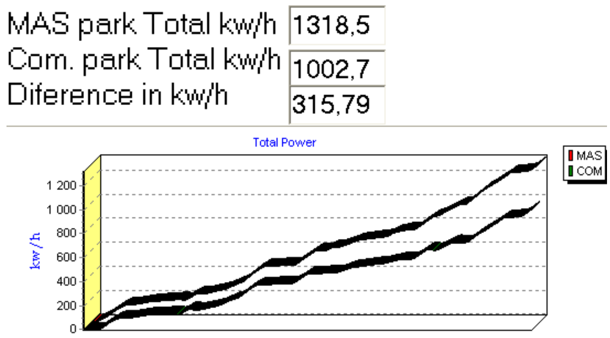

Figure 8 Comparison between powers MAS and Typical controls

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