Control Algorithm for Coordinated Reactive Power Compensation in a Wind Park

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***Abstract*—The penetration level of wind energy is continuously growing, and it is especially relevant in European countries such as Denmark, Germany, and Spain. For this reason, grid codes in different countries have been recently revised, or are now under revision in order to integrate this energy in the network taking into account the security of supply. This paper is related to reactive compensation, which is one aspect usually included in these codes. On the other hand, a great number of installed wind parks are formed by fixed speed wind turbines equipped with induction generators. The typical scheme for reactive compensation in this kind of wind parks is based on capacitor banks locally controlled in each machine. This configuration makes very difficult to follow the requirements of the new grid codes. To overcome this problem, a configuration with a central controller that coordinates the actuation over all the capacitor steps in the wind park is proposed in this paper. A central controller algorithm that is based on a dynamic programming is presented and evaluated by means of simulation. At this time, the proposed scheme has been installed at the Sotavento Experimental Wind Park (Spain) and it is currently being tested.**

***Index Terms*—Dynamic programming, reactive power control, wind energy.**

I. INTRODUCTION

FROM last years findings, the presence of wind energy in the generation share has been continuously increasing. During 2005, the average annual penetration level for wind energy was approximately 23% in West Denmark, 8% in Spain, and 5% in Germany. These levels represent a serious challenge for the electrical grids due to the nature of wind and the technology of wind turbines.

Transmission system operators (TSOs) must adapt their grid codes for enabling wind generation to connect to the transmission ensuring the security of supply. Active power control, frequency control, voltage control, reactive power compensation, or voltage sag immunity are aspects that have been regulated in different grid codes around the world. The main focus of this paper is the reactive power compensation, which is a common aspect regulated by the TSO's in Spain, Germany, Denmark, Scotland, etc. [2]–[5].

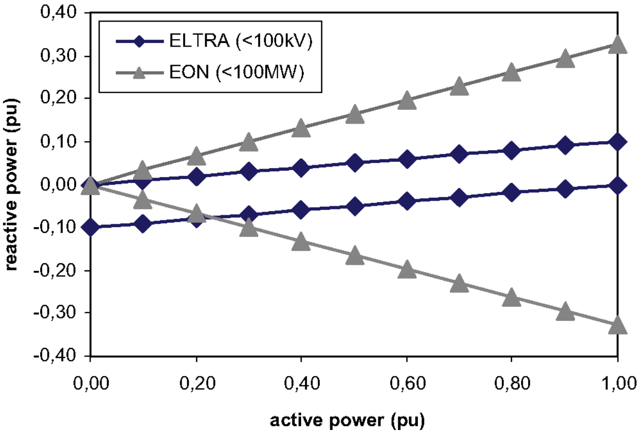

Fig. 1. Reactive compensation in ELTRA and EON grid codes.

An important amount of the wind turbines currently operating around the world are fixed speed ones based on conventional cage induction generators, e.g., in Spain, the installed capacity of this technology was 34% in 2006, and in Denmark, it was more than 70% in 2005.

The reactive compensation in wind parks formed by this type of machines is commonly done through capacitors banks, which are divided in steps, installed in the low voltage (LV) side of wind turbines and in the medium voltage (MV) side of substation [1]. Each set of capacitors is controlled by its own power factor controller (PFC), which could be embedded in the control circuits of wind turbines or as a separate device.

In early years, compensation systems was typically designed to achieve a unitary cos φ calculated on a large basis, e.g., from monthly active and reactive energy. This was done by adjusting the set point cos φ in each PFC to a unitary value.

Nowadays, TSO grid codes impose different reactive compensation strategies. Next, there are examples of reactive requirements in the European countries with more installed wind power.

1) In E.ON network (Germany), each wind park with a rated power of $<$100 MW must be able to operate with a power factor from 0.95 inductive to 0.95 capacitive (see Fig. 1). The operating point for the reactive exchange is determined by the TSO and the new working point must be attained within a minute [4].
2) In REE network (Spain), wind parks specifications for the reactive power ranges are not obligatory, but an incentive or penalty complement depending on the achievement of specified cos ϕ is applied [5]. The cos ϕ, and so the incentive payment, was calculated every 60 min from the active and reactive energy during this period. They depend on the time of the day as shown in Table I.

Manuscript received January 9, 2008. Current version published November 21, 2008. This work was supported by Sotavento Galicia, S.A. as part of a research project and by the "Dirección General de Investigación" of the Ministerio de Educación y Ciencia with the project "Problematica de la integración de la energía eólica en la red eléctrica: el caso de Galicia" (ENE2007-67473). Paper no. TEC-00001-2008.

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Digital Object Identifier 10.1109/TEC.2008.2001432

TABLE I
INCENTIVE PAYMENT FOR REACTIVE COMPENSATION IN SPANISH WIND PARKS

	cos φ	Incentive (%)		
		Peak	Flat	Valley
Inductive	<0,95	-4	-4	8
	<0,96 and 0,95	-3	0	6
	<0,97 and 0,96	-2	0	4
	<0,98 and 0,97	-1	0	2
	<1,00 and 0,98	0	2	0
	1,00	0	4	0
Capacitive	<1,00 and 0,98	0	2	0
	<0,98 and 0,97	2	0	-1
	<0,97 and 0,96	4	0	-2
	<0,96 and 0,95	6	0	-3
	<0,95	8	-4	-4

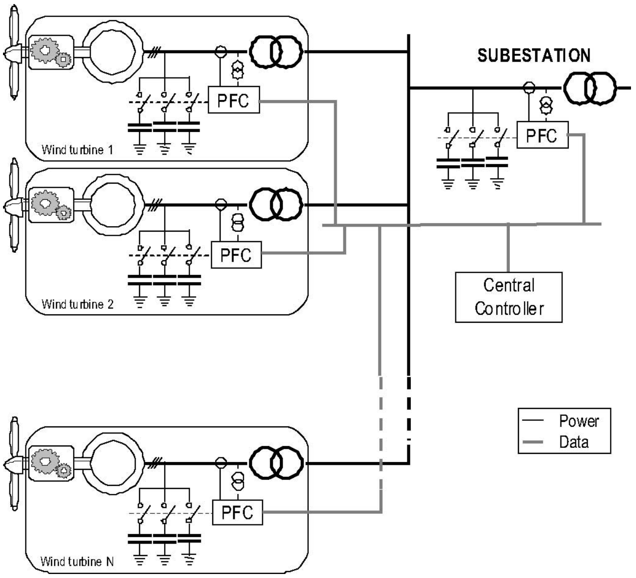

Fig. 2. Wind park with a central controller for reactive compensation.

3) In Eltra/Elkraft network (Denmark), for wind parks connected to grid voltages below 100 kV, the reactive power, averaged over 5 min, that a wind turbine (including wind turbine transformer) exchanges with a grid must lie within the control band shown in Fig. 1 unless the exchanged power is less than 25 kVAr [3].

FACTS [e.g., static compensator (STATCOM)] are usually shown as the only alternative in wind parks formed by fixed speed wind turbines to fulfil the grid code requirements on reactive compensation or voltage control [6].

In this paper, the following alternative is presented; it consists in coordinating the actuation of all the PFC installed in the wind park by means of a central controller [7], [8]. In this way, actuation of each PFC can be adjusted in real time and independently in order to achieve a specific wind park cos φ or a reactive power as close as possible to the objective (see Fig. 2). A central controller algorithm with the ability to coordinate the actuation over all capacitor steps must be developed.

A control algorithm for the central controller is proposed in this study. Due to simulations, the behavior of this system is evaluated against simpler solutions.

This scheme is installed at the Sotavento experimental wind park (http://www.sotaventogalicia.com) located in Galicia (northwest of Spain) [9]. At present, the algorithm has already been implemented in the central controller and it is currently being tested.

II. ALGORITHM FOR THE CENTRAL CONTROLLER

The system shown in Fig. 2 is a centralized one, in which actions of all PFC's (located at wind turbines and substation) are coordinated by means of a central controller. The proposed algorithm for this controller works following these steps.

1) In each moment, the reactive power to be generated by the capacitors banks installed in the whole wind park must be calculated. This capacitive reactive power is obtained from the objective of reactive power or cos ϕ for the wind park in each period.
2) This amount of reactive power must be distributed between the capacitor banks of the substation and the ones of the wind turbines. This must be done by minimizing the number of operations over the substation capacitor banks.
3) In this step, the total amount of reactive power that must be generated in all the capacitor banks of all wind turbines is distributed between each wind turbine. An optimization function that takes into account the available capacitors and the active power generated in each wind turbine has been used.
4) Finally, the required states of the capacitor steps must be sent to the PFC's.

A. *Working Cycle and Capacitive Reactive Power Calculation*

The algorithm of the central controller runs in a cyclic way. Every cycle of the algorithm must last a period of time, which is called a segment, less than the time necessary to achieve the objective. For example, in Spain, the cos φ is calculated in periods of 60 min, so that the length of the segment must be a fraction of this time. The segment length, or the number of segments in each period, must be optimized so as to get a balance between achievement of the objective, cos φ or reactive power, and the number of capacitor steps connections. The response of PFC's and the frequency of measurements also have a strong influence on its value.

At the end of each segment, a reactive power error is calculated as the deviation from objective using

$$\Delta Q^{(s} = Q_{\mathrm{obj}} - Q^{(s} \tag{1}$$

where

Q_{obj} objective reactive power to be generated by the wind park during the current period;
$Q^{(s}$ reactive power generated during the segment "s";
$\Delta Q^{(s}$ reactive power deviation from the objective during the segment "s."

At the end of each segment "s," the capacitive reactive power to be generated in the following segment is calculated from

$$Q_{c,\mathrm{obj}}^{(s+1} = \Delta Q^{(s} + Q_c^{(s} \tag{2}$$

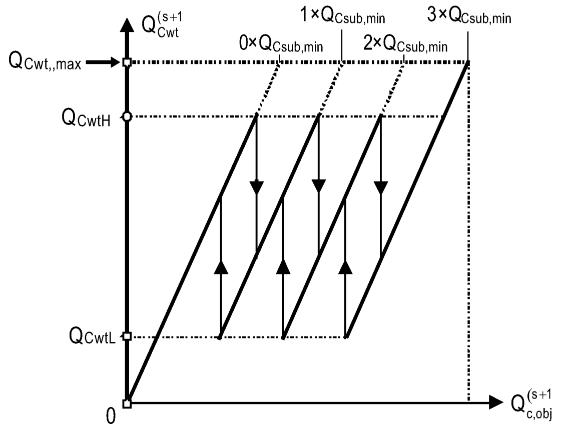

Fig. 3. Hysteresis process to allocate the required reactive power between substation and wind turbines.

where

$Q_c^{(s}$ capacitive reactive power generated by the wind park capacitors during the segments "s," calculated from the state of all capacitor steps (in wind turbines and in substation);

$Q_{c,\mathrm{obj}}^{(s+1}$ objective of capacitive reactive power to be generated by the wind park capacitors during the segment "$s+1$."

With this compensation strategy, the maximum reactive deviation from the required value in each period is

$$\sum_{s=1}^{N_s} \Delta Q^{(s} = \Delta Q^{(1} - \Delta Q^{(N_s} \tag{3}$$

where N_s is the number of segments in each period.

B. Capacitive Reactive Power in Substation and Wind Turbines

In the previous paragraph, the amount of capacitive reactive power $Q_{c,\mathrm{obj}}^{(s+1}$ to be injected by the whole wind park in the segment "$s+1$" has been calculated. The next step is to allocate this power between the substation and the wind turbines capacitors, so

$$Q_{c,\mathrm{obj}}^{(s+1} = Q_{\mathrm{Csub}}^{(s+1} + Q_{\mathrm{Cwt}}^{(s+1} \tag{4}$$

where $Q_{\mathrm{Csub}}^{(s+1}$ is the capacitive reactive power to be generated in the substation and $Q_{\mathrm{Cwt}}^{(s+1}$ is the reactive power to be generated in the set of wind turbines.

Usually, substation capacitors are installed in the MV side, this fact reduces the number of connection operations that can be done in their steps, besides, their discharge can last several min. As a consequence, the capacitor steps in wind turbines, normally installed in the LV side, must be used more dynamical in order to fulfill (4).

Taking into account this restriction, the reactive sharing between substation and wind turbines is done through a hysteresis process, as can be seen in Fig. 3, where:

1) $Q_{\mathrm{Csub,min}}$ is the reactive power for minimum step of substation capacitors battery.
2) $0 \times Q_{\mathrm{Csub,min}}$, $1 \times Q_{\mathrm{Csub,min}}$, $2 \times Q_{\mathrm{Csub,min}}$, and $3 \times Q_{\mathrm{Csub,min}}$ represent the achievable reactive power values for two steps with equal nominal power. It must be noted that these achievable values depend on the size of steps installed on substation.
3) $Q_{\mathrm{Cwt,max}}$ is the total capacitive reactive power that could be generated by connecting all the capacitor steps in all the wind turbines.
4) Q_{CwtL} and Q_{CwtH} are the low and high limits for the capacitive reactive power to be generated by the wind turbines.

With the aim of getting a solution for the allocation with the hysteresis process shown in Fig. 3, the next rules must be followed.

1) Operations over the substations capacitor steps are only done when the total wind turbine reactive is out of the limits Q_{CwtL} and Q_{CwtH}.
2) When a change in the state of substation steps is necessary, the solution to the new values for substation reactive power $Q_{\mathrm{Csub}}^{(s+1}$ and total wind turbine reactive power $Q_{\mathrm{Cwt}}^{(s+1}$ will be as far as possible from the limits Q_{CwtL} and Q_{CwtH}.
3) The central controller must estimate the time left to accomplish the complete capacitor discharge. So, only discharged steps will be considered when the solution to (4) is calculated.
4) When a solution to the allocation is not found (e.g., when some capacitors are discharging), the closest one is chosen.

C. Wind Turbine Reactive Allocation

In previous paragraphs, the amount of reactive power $Q_{\mathrm{Cwt}}^{(s+1}$ to be generated by all the capacitor steps installed in wind turbines has been calculated. Now, it is necessary to distribute this reactive power between each wind turbine using an optimization algorithm. Dynamic programming has been used in the optimization process, its associated cost function takes into account the number of capacitor steps to be connected or disconnected and the power delivered by the wind turbine [10]–[12]. In this way, the desired reactive power is achieved with a minimum of capacitor steps operations.

1) Discretization and Cost Function: Once the total capacitive reactive power $Q_{\mathrm{Cwt}}^{(s+1}$ is calculated, as shown earlier, the next task is to distribute it between the capacitor steps of each wind turbine.

In a wind turbine, the capacitive reactive power generated depends on the state of the capacitor steps. So, there are 2^N possible step combinations for a wind turbine with N steps, although there are only N different reactive power values if all the steps have the same size. The number of step combinations exponentially increase with the number of steps, especially if all the capacitors of each wind turbines are treated as a whole set of capacitor steps. In this way, for a certain $Q_{\mathrm{Cwt}}^{(s}$ value could exist a great deal of step states of wind turbines combinations that generate this reactive power. This makes difficult to calculate a set of optimal step states for the entire wind park. To cope with this problem, an optimization method based on dynamic programming is proposed in the next paragraphs.

In order to decrease the number of operations to calculate an allocation solution, the space of possible values of $Q_{\mathrm{Cwt}}^{(s+1}$ is discretized. Thus, any value of $Q_{\mathrm{Cwt}}^{(s+1}$ is corrected with the expression

$$Q_{\mathrm{Cwt}}^{(s+1} = \mathrm{round}\left\{\frac{Q_{\mathrm{Cwt}}^{(s+1}}{Q_{\min}}\right\} \times Q_{\min} \tag{5}$$

where $Q_{\min}$ is a reactive value used to discretizing, it could be the maximum common divider for all the capacitor steps in all wind park.

For each wind turbine "i," a vector called $\boldsymbol{Q}_{\mathbf{Cwt},\boldsymbol{i}}^{(\boldsymbol{s}+\mathbf{1}}$ with $Nc_i + 1$ elements is calculated, where

$$Nc_i \approx \frac{Q_{\mathrm{total}}, i}{Q_{\min}} + 1 \tag{6}$$

and $Q_{\mathrm{total,i}}$ is the maximum reactive power that can be generated by the capacitors installed on the wind turbine "i."

Each vector element, from 0 to N_{Ci}, has associated a reactive power calculated as $k \times Q_{\min}$, where k is the position of the vector element. The value for a k-element is calculated by means of a cost function, defined next, only if the corresponding capacitive reactive power is achievable with the capacitor steps installed in the wind turbine "i." So, the elements $\boldsymbol{Q}_{\mathbf{Cwt},\boldsymbol{i}}^{(\boldsymbol{s}+\mathbf{1}}$ are defined as

$$\boldsymbol{Q}_{\mathbf{Cwt},\boldsymbol{i}}^{(\boldsymbol{s}+\mathbf{1}}(k) = \begin{cases} \Psi_{k,i}, & \text{if } \exists j \in \{1,\ldots,2^{N_i}\} | \sum\limits_{r=1}^{N_i} \boldsymbol{E_{i,j}}(r) Qs_{i,r} = kQ_{\min} \\ \text{null}, & \text{otherwise} \end{cases} \tag{7}$$

where the parameters are follows.

1) N_i is number of capacitor steps in the wind turbine "i."
2) $\boldsymbol{E_{i,j}}$ is a $N_i \times 1$ vector whose elements represent a possible state of the capacitor steps in the wind turbine "i." The "0" value represents a disconnected step, and "1" represents a connected one.
3) $Qs_{i,r}$ is the capacitive reactive power for the step "r" in the windturbine "i."
4) $\Psi_{k,i}$ is a cost function that will be defined next.

The cost function is the value to be optimized and it is defined as

$$\Psi_{k,i} = N\mathrm{Op}_{\min,k} + 10^{-3} \cdot \left(k \cdot Q_{\min} - T_i \cdot \frac{P_i^{(s} - P_{Ni}}{P_{Ni}}\right)^2 \tag{8}$$

where

T_i	constant;
P_{Ni}	nominal power for the wind turbine "i";
$P_i^{(s}$	mean power generated by wind turbine "i" during the segment "s";
$N_{\mathrm{Opmin},k}$	minimum step states changes to achieve the reactive $k \times Q_{\min}$.

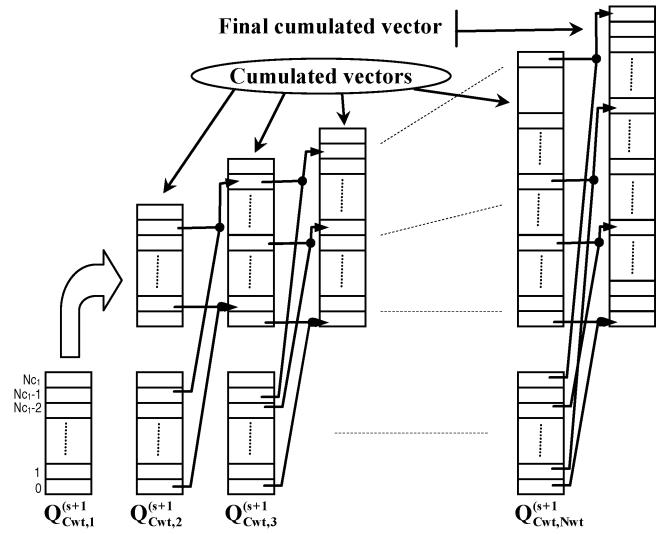

Fig. 4. Optimization process.

Thus,

$$N\mathrm{Op}_k = \min\{\mathrm{sum}(\mathrm{xor}\{\boldsymbol{E}_{\boldsymbol{i}}^{(s}, \boldsymbol{E_{i,j}}\})\}_{j\in\{1,\ldots,2^{N_i}\}} \tag{9}$$

where $\boldsymbol{E}_{\boldsymbol{i}}^{(s}$ represents the step states at the end of segment "s."

The cost function has two terms, as shown in (8). One term is related to the operations number, so, the optimization of this function will guarantee that the number of operations over the capacitor steps will be minimized. The second one is intended to achieve that those wind turbines that are generating more active power can also be the ones generating more capacitive reactive power.

2) Optimization Process: In previous paragraphs, a set of vectors $\boldsymbol{Q}_{\mathbf{Cwt},\boldsymbol{i}}^{(\boldsymbol{s}+\mathbf{1}}$ for each wind turbine has been calculated. These vectors will be used for the optimization process that calculates the allocation of the total wind turbine reactive power $Q_{\mathrm{Cwt}}^{(s+1}$ between all the capacitor steps in wind turbines.

Owing to a dynamic programming method, a set of cumulated vectors is created (see Fig. 4). The first cumulated vector is equal to $\boldsymbol{Q}_{\mathbf{Cwt},\mathbf{1}}^{(\boldsymbol{s}+\mathbf{1}}$ for the wind turbine "1," and the next ones are calculated following these steps.

1) The elements of the new cumulated vector are calculated from the combination between the no-null elements of previous cumulated vector and the next $\boldsymbol{Q}_{\mathbf{Cwt},\boldsymbol{i}}^{(\boldsymbol{s}+\mathbf{1}}$ vector. The position in the vector is associated to capacitive reactive power, so that the new element's position is obtained summing the previous cumulated vector plus the wind turbine vector's positions.
2) The new element's cost is calculated summing the costs of the elements that generate it.
3) The final cost of the new element is the minimum value of the costs calculated in the previous point.
4) The final cumulated vector has no-null values related to all the possible capacitive reactive power values that can be obtained by any combination of all capacitor steps installed in wind turbines. The size of this vector can be

calculated with

$$Nc \approx 1 + \frac{\sum_{i=1}^{N_{wt}} Q_{\mathrm{total},i}}{Q_{\min}}. \tag{10}$$

The value of each no-null element of the final cumulated vector is the optimum cost for associated reactive power. Hence, for any reactive power value or element in the final vector, the related step states in each wind turbine can be calculated, and they will be the ones that optimize the capacitor operation number and the sharing of capacitive reactive power.

As a conclusion, for total wind turbine reactive power value $Q_{\mathrm{Cwt}}^{(s+1}$, the element (k_{sel}) that must be selected in the final vector is

$$k_{\mathrm{sel}} \approx \frac{Q_{\mathrm{Cwt}}}{Q_{\min}}. \tag{11}$$

Then, the step states in each wind turbine that generates the optimum value for this element must be calculated, and the following equation must be fulfilled

$$Q_{\mathrm{Cwt}}^{(s+1} = \sum_{i=1}^{N_{\mathrm{wt}}} Q_{\mathrm{Cwt},i}^{(s+1} \tag{12}$$

where $Q_{\mathrm{Cwt},i}^{(s+1}$ represents the optimum value for the capacitive reactive power to be generated in wind turbine "i."

Each optimum value $Q_{\mathrm{Cwt},i}^{(s+1}$ could have associated more than one step state vector. In the following paragraphs, a selection method is presented with the aim of eventually deciding the required state for the steps in each wind turbine.

3) Optimum Step States: The central controller must send the desired step states to each PFC, installed in substation and wind turbines, in order to achieve the required reactive compensation.

In the preceding paragraphs, the capacitive reactive power $Q_{\mathrm{Csub}}^{(s+1}$ required in the substation during the segment "$s + 1$" and the corresponding reactive capacitive power to be generated in each wind turbine $Q_{\mathrm{Cwt},i}^{(s+1}$ have been calculated. The next step is to calculate the states of capacitor steps so as to get the mentioned reactive power.

In the substation, the number of capacitor steps is usually low. In this case, the required state for them can be easily calculated; nevertheless, the capacitors discharge time must be respected when deciding the steps that must be connected.

In the case of wind turbine capacitors, since the typical discharge time for LV capacitors is lower than 1 min, the estimation of discharge state could be overcome if the duration of the segment (T_s) was large enough.

Finally, it is necessary to calculate the step states vector for each wind turbine. As shown in previous paragraphs, an optimum wind turbine reactive power $Q_{\mathrm{Cwt},i}^{(s+1}$ could have several step state vectors with the same reactive power. This states are defined as

$$\left\{\boldsymbol{E}_{\boldsymbol{i},\boldsymbol{1}}^{\mathbf{opt}}, \boldsymbol{E}_{\boldsymbol{i},\boldsymbol{2}}^{\mathbf{opt}}, \mathbf{K}\right\} \tag{13}$$

TABLE II
WIND TURBINES INSTALLED IN THE SOTAVENTO WIND PARK

Wind Turbine Model	Nº	Power (kW)	Pitch / Speed
Izar-Bonus 1.3 Mw	1	1300	Variable / Fixed
Made AE - 46	4	660	Fixed / Fixed
Neg Micon NM-750	4	750	Fixed / Fixed
Neg Micon NM-900	1	900	Fixed / Fixed
Ecotecnia 44 - 640	4	640	Fixed / Fixed
Made AE-52	1	800	Variable / Variable
Izar-Bonus MK - IV	4	600	Fixed / Fixed
Gamesa G-47	4	660	Variable / Variable
Made AE - 61	1	1320	Fixed / Fixed

where

$$Q_{\mathrm{Cwt},i}^{(s+1} = \sum_{r=1}^{N_i} \boldsymbol{E}_{\boldsymbol{i},\boldsymbol{m}}^{\mathbf{opt}}(r)\, Qs_{i,r}. \tag{14}$$

The selected step state vector is one that minimizes these values.

1) The number of state changes between a step states vector and step states at the end of segment "s."
2) The number of accumulated connection operations, typically PFC's take account of these values, for the capacitor steps to be connected and/or disconnected.

In order to decide which step state vector is more appropriate, a selection between vectors is done by means of the aforementioned rules.

Due to the the selection process depicted earlier, the accumulated number of connection step operations will be balanced between the capacitor steps of the same size in each wind turbine.

III. SOTAVENTO EXPERIMENTAL WIND PARK

The algorithm depicted in this paper is being implemented at the Sotavento experimental wind park. The project, called Sotavento Galicia S. A. [9], was born in 1997 promoted by the Consellería de Industria e Comercio (Department for Industry and Trade), one of the departments of Xunta de Galicia (local government). Its objective is still to obtain not only economic but also scientific and technical benefits. Three public institutions are taking part in this project with a total amount of 51% of its capital.

The Sotavento experimental wind park has installed 24 wind turbines (see Table II) with a total power of 17.56 MW and an estimated annual energy production of 38.5 GW·h.

IV. SIMULATION

The behavior of the Sotavento experimental wind park with the reactive compensation configuration, shown in Fig. 2, and the central controller introduced in this paper are evaluated through simulation. A wind park model and a PFC model are needed, and therefore, presented in the next paragraphs.

A. Wind Park Model

Wind park has been modeled from the measurement data given by the Sotavento experimental wind park. The active and

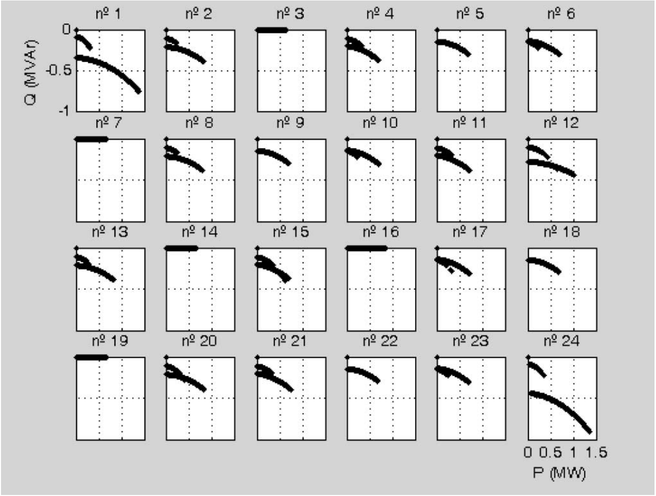

Fig. 5. PQ curves from wind turbines.

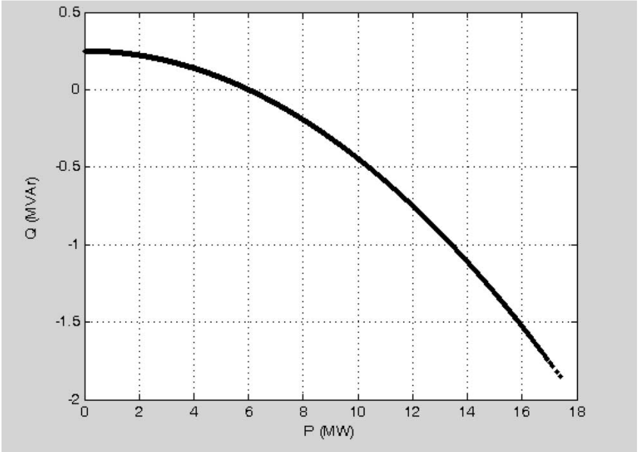

Fig. 6. Reactive losses versus the power generated by the wind park.

reactive curves for each wind turbines have been calculated from these measurements; the results can be seen in Fig. 5.

In addition, the losses in lines and transformer have also been modeled as a function of the power generated by the wind park, as shown in Fig. 6.

B. PFC Model

In the Sotavento experimental wind park, a commercial PFC device has been installed in the substation and in all the wind turbines that will participate in the centralized reactive compensation. A model for this device has been done by means of laboratory tests. The agreement between the measured behavior and the simulated one when the PFC is installed in a wind turbine can be observed in Fig. 7. In this figure, the following values are plotted: power delivered by the wind turbine, the simulated cos φ, the measured cos φ, and the cos φ set point.

V. RESULTS

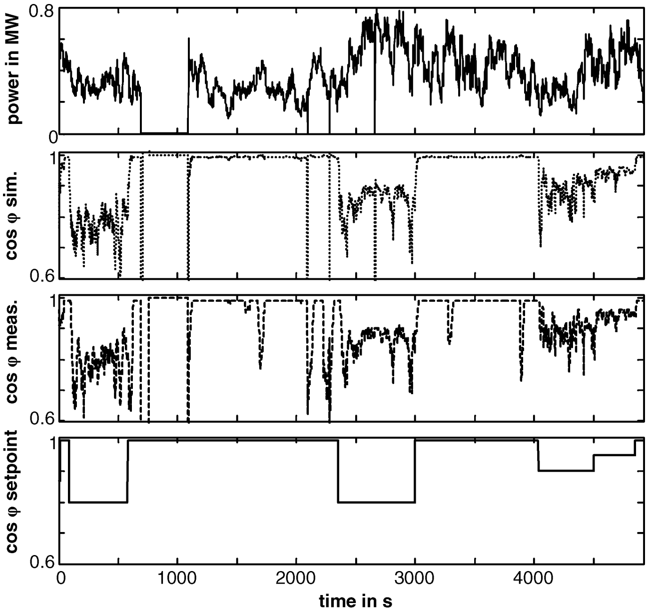

Fig. 7. PFC simulation results.

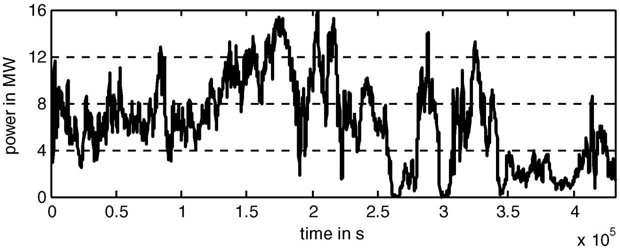

Fig. 8. Power generated by the wind park (measured in substation).

The central controller algorithm for the system depicted in Fig. 2 has been introduced in previous sections. In order to evaluate the benefits of this centralized configuration, a comparison against a local controlled system is done. In this local scheme, the reactive compensation is locally done with the PFC installed in each wind turbine and in the substation. The cos φ set point for all PFC's is the same, and it is controlled by a timer, the set points are adjusted to the maximum payment values shown in Table I.

The data for simulation, active, and reactive power in substation and wind turbines, have been obtained from five days measurements given by the Sotavento experimental wind park. As an example, the wind park power used during the simulation can be seen in Fig. 8.

The simulation results for the proposed central system are called central, and the results for the local controlled system are known as local; both can be observed from Figs. 9–14.

For the sake of understanding the results in an easy way, during the simulation, the objective cos φ has been considered constant, so, different simulations have been done for flat, valley, and peak situations.

The reactive power generated by the wind park during a flat period is shown in Fig. 9. The results for the central system are closer to the objective than those for the local system. The same behavior can be seen in Fig. 10 where the incentive payment and cos φ for each 60 min period is shown [5].

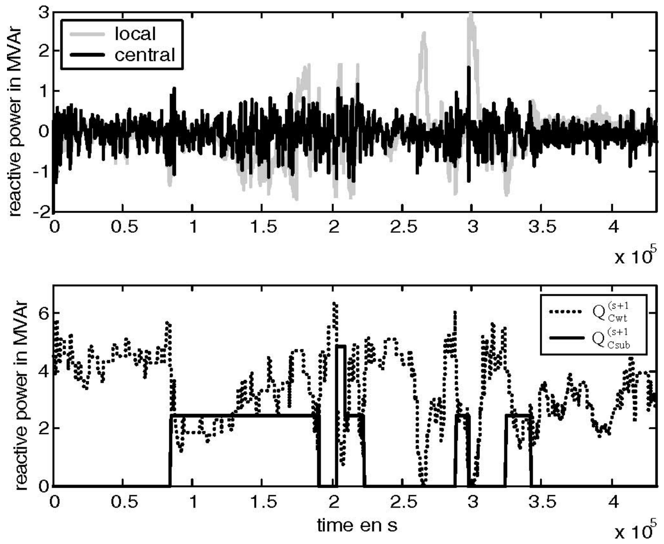

Fig. 9. Reactive power generated by the wind park (flat).

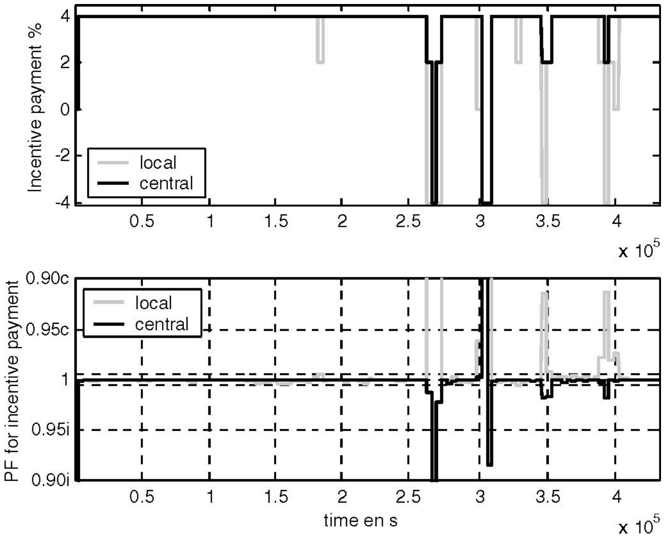

Fig. 10. Incentive payment and cos φ for each 60 min period (flat).

The results for the capacitive reactive power in the substation and total reactive power for the wind turbines are shown in Fig. 9. As can be checked, the capacitors in wind turbines are more dynamically treated than those in substation.

Figs. 11–13 show active power versus reactive power and the limit for the objective cos φ (see Table I). In all the situations (flat, valley, and peak), the results for central system are closer to the desired value than those for the local system.

Finally, Fig. 14 shows the accumulated connection operation number for each step in a wind turbine whose steps have the same reactive power. The operation number is balanced between all the steps due to the actuation of the central algorithm.

A summary of simulation results is presented in Table III, where the total incentive payments during the simulation period and the total number of connection operations for all the steps in the wind park are displayed. As can be seen, the reduction of operation number for the central system is higher than 70%

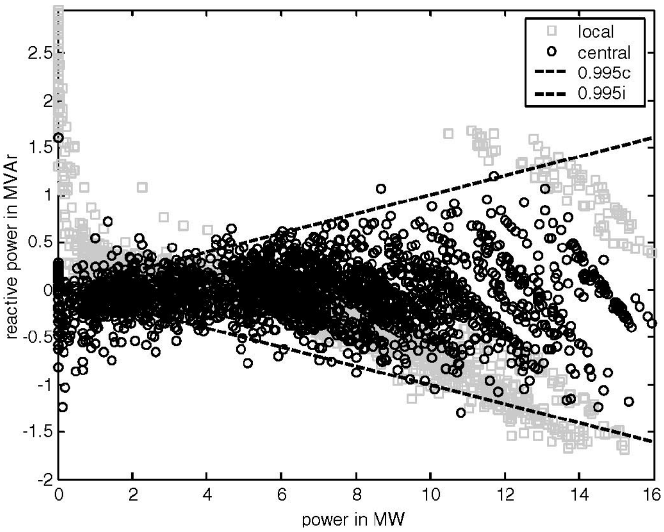

Fig. 11. Active power versus reactive power (flat).

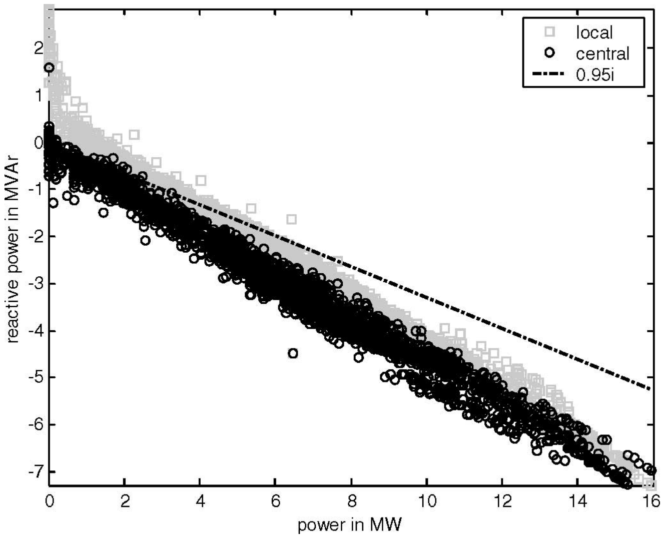

Fig. 12. Active power versus reactive power (valley).

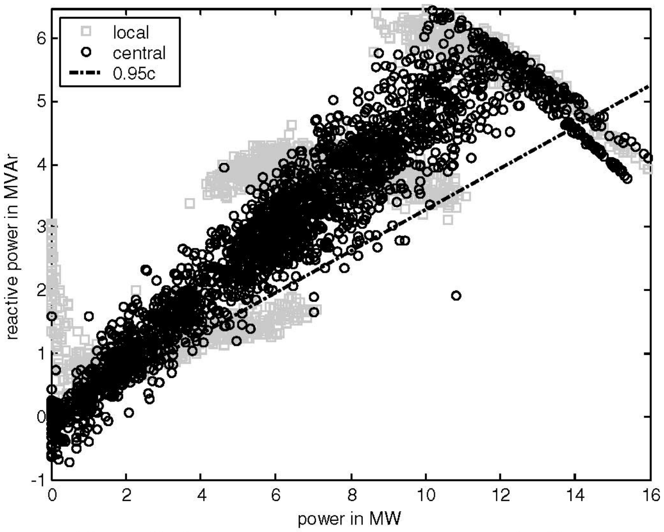

Fig. 13. Active power versus reactive power (peak).

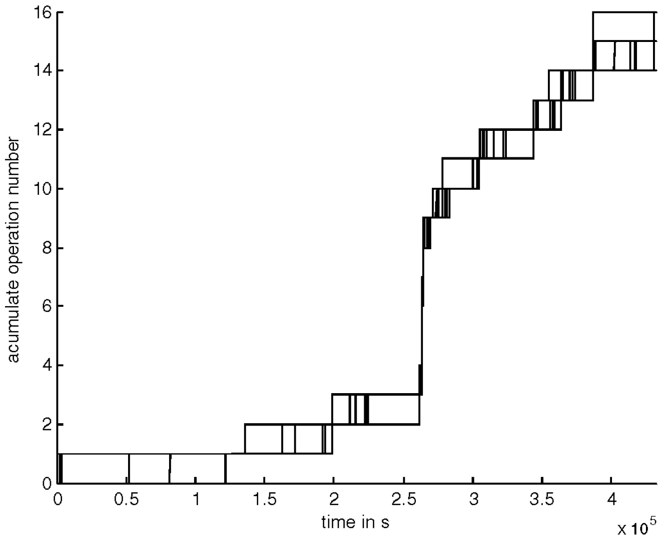

Fig. 14. Number of step connection operations in a wind turbine with capacitor steps of the same size.

TABLE III
SIMULATION RESULTS

Incentive Payment (%)	Operation Number	Reg.	Period
3,98	5127	Central	Flat
3,86	25578	Local	
7,77	7678	Central	Peak
7,45	34393	Local	
8,00	3434	Central	Valley
7,53	33734	Local	

when compared to the local system. Furthermore, the incentive payment has been increased more than 3%.

It must be noted that the achievement of a cos φ in low generation situations is influenced by the stops of wind turbines at low wind conditions. Moreover, in peak periods with high generation, the amount of installed capacitive power limits the achievable cos φ.

VI. CONCLUSION

In this study, a scheme for reactive compensation in wind parks is depicted. The system is based on the coordination of all capacitor steps in wind turbines and substation by means of a central controller. All local PFC's continuously receive the desired state for its capacitor steps from the central controller.

The algorithm for the central controller is presented here. Its main objective is to achieve the specific wind park objective, cos φ, or reactive power value with the minimum number of capacitor steps operations. Furthermore, the operations in substation capacitor steps are taken into account with a preselection process.

The main conclusions of this paper are as follows.

1) The behavior of the central system is compared to a local one by means of simulation.
2) Modeling of PFC's and wind park has been done through real measurements and laboratory tests.
3) With the central controller algorithm, the achievement of a specific cos ϕ is higher than that achieved with a local scheme. Besides the number of operations over the capacitor steps is highly reduced.
4) The number of operations in substation has been specially reduced with the central system.
5) The accumulated steps operation in a wind turbine has been balanced so that capacitor steps of same size have a similar number of operations.

The central scheme for reactive compensation as shown in Fig. 2 has already been implemented at the Sotavento experimental wind park; at this time, the algorithm for the central controller is currently being tested.

ACKNOWLEDGMENT

The authors would like to thank the personnel of Sotavento experimental wind park for their contribution and help with field experience, and for their accessibility to the measurement data.

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