Finding Optimum Reactive Power Compensation in a Wind Farm

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Abstract. Presently, renewable energies and especially wind energy are gaining a special relevance in the electrical market worldwide. This is due to the more and more urgent need to find alternative energies that supplant those derived from fossil fuels. Within this present framework of renewable energy development, it is worthy of mention the rapid advancement of wind energy and its notable penetration into the electrical systems of different countries, both in Europe and worldwide.

This current rate of growth motivates the wind farms to not limit themselves to producing energy, but also to provide stability to the network within its capabilities, making then possible to increase the power percentage relative to the total power of the system. So, actual objective is to adapt the installations that produce wind energy in such a way that they give a maximum amount of support in any given moment to the electrical network.

Throughout this study a complete cost-benefit analysis model is developed, focused on incorporating automatic capacitor banks into wind farms for the compensation of reactive power. The used methodology can be applied to the other technologies as well by simply amplifying the algorithms according to the specific characteristics of the option elected.

Key words

Wind Energy, Reactive Power Compensation, Power Factor Correction, Optimisation, Optimum system sizing

1. Introduction

Presently, renewable energies and especially wind energy are gaining a special relevance in the electrical market worldwide. This is due to the more and more urgent need to find alternative energies that supplant those derived from fossil fuels [1]. Within this present framework of renewable energy development, it is worthy of mention the rapid advancement of wind energy and its notable penetration into the electrical systems of different countries, both in Europe [2] and worldwide [3]. Also, it is remarkable the actual predictions of development for the years 2010 and 2020 [4]. Within the European Union, the countries with the greatest levels of wind-generated power currently are Germany (18.428 MW), Spain (10.027 MW) and Denmark (3.122 MW).

The participation of wind energy in the worldwide electricity supply has reached 0.4 %. In the E.U., 4 % [5] of the power instalments are wind-generated and in Spain, 9% [6]. Current predictions anticipate wind energy providing 12 % of the global demand for electricity by the year 2020 [7].

The most significant environmental benefit that wind energy would provide is the reduction of carbon dioxide emitted into the Earth's atmosphere. Carbon dioxide is the principal gas responsible for the increase of the greenhouse effect (Table I), which threatens with disastrous consequences in terms of a global climate change [8]. Assuming that the average value of carbon dioxide avoided by changing over to wind energy is 600 tons per GWH, the annual decrease according to this scenario would be 1.856 million tons of $C0_2$ in 2020 and 4.800 million tons in 2040. This would represent 50.7% of CO_2 emissions released into the atmosphere in 2020 since the amount of CO_2 emissions is estimated at 3608 million tons. The accumulated reduction would be 11.768 million tons of CO_2 in 2020 and 86.469 million tons in 2040 [9]. Europe provides nearly 73% of wind-generated power worldwide, thanks to its firm and consistent policies aimed to increase the demand of renewable-energy technologies.

TABLE I. - Energy Indicators in the European Union

Year	Population	Electricity Generated per capita	CO_2 emissions per capita	Dependency on importation
2000	377,7	6702,7	8,7	52,0
2010	383,0	7525,7	9,0	59,1
2020	383,5	8269,3	9,4	65,9

From the above, the necessity to continue increasing and developing wind energy as a clean source of electrical energy production can be appreciate. Therefore, new problems related to the management and operation of energy transfer and distribution, and to the efficient distribution of renewable energy in the grids, are actually arising [10]. These problems bring with them the need for the various wind farms to not limit themselves to produce energy, but also to provide stability to the network within its capabilities, of such a form that it will be possible to increase the percentage of power installments relative to the total power of the system. To achieve this goal, different regulations are being put into effect in this area, in the same way that other regulations have been put into effect with the aim of increasing the development of wind energy.

This article studies various propositions and demonstrates the viability of one of them that tends to allow the regulation of the reactive energy according to the necessities of the transportation networks of the electrical system. Throughout this study, it is our intention to find the optimum value which is attainable within the given proposition, as well as to assess the influence of the diverse parameters that directly affect the case in study.

2. Current Legislation in the European Union

Presently, the regulation that governs the different aspects concerning power quality is EN-50.160. This standard focuses exclusively on the voltage quality and includes a series of definitions and limit-values for the different disturbances that can take place in an electric network. Another set of complementary standards that help to clear up different aspects of wave quality and the measurement thereof are:

· IEC 61000-4-30: Defines the different methods of measurement for the various established parameters.
· IEC 61000-4-7: Establishes the measuring procedures of the harmonics and interharmonics.
· IEC 61000-4-15: Determines the functional specifications and the design of the flicker measurer (flickermeter).

Also, there is a regulation relative to the wave quality in the systems of wind generation:

· IEC 614000-21: Defines the form of measure and evaluation of the delivery quality of the wind turbines connected to the network.

In the Spanish legislation, it is important to note the decree RD 436/2004 [11] that establishes the new requirements for the connection to the network. Before this decree, the only specifications that were necessary to comply with in order to be able to establish a connection with the electrical network was to have a power installment with less than 5% of the shortcircuit power at the connection point, and to maintain a power factor close to the unit.

Now, in the light of the importance of the production of wind energy and its integration into power networks with a percentage of electricity production from windpower of 5%, a more global contribution to the network is required, not only in terms of production but also in terms of help or support to the networks of transportation and distribution. Within the various possibilities of providing support to the network, there are two that are fundamental:

1) *Compensation of the Reactive Power*: Before, Spanish legislation only required that wind farms maintain a unity power factor to reach a 4% bonus, however, now the maximum bonus has been established at 8%, but according to the following chart (Table II).

TABLE II.- Bonus by power factor

TYPE	POWER FACTOR	BONUS (%)		
		Peak	*Normal*	*Valley*
INDUCTIVE	<0,95	-4	-4	8
	0,95>= cos Phi <0,96	-3	0	6
	0,96>= cos Phi <0,97	-2	0	4
	0,97>= cos Phi <0,98	-1	0	2
	0,98>= cos Phi <1	0	2	0
	1	0	4	0
CAPACITIVE	0,98>= cos Phi <1	0	2	0
	0,97>= cos Phi <0,98	2	0	-1
	0,96>= cos Phi <0,97	4	0	-2
	0,95>= cos Phi <0,96	6	0	-3
	<0,95	8	-4	-4

2) *Maintenance of the connection during tension gaps*: 5% bonus for those installations that are capable of maintaining continuity of supply during tension gaps. The current curve established by REE with which the different installations must comply, as a minimum requisite, to guarantee the constant supply of energy in case of a tension gap, can be see in Fig. 1.

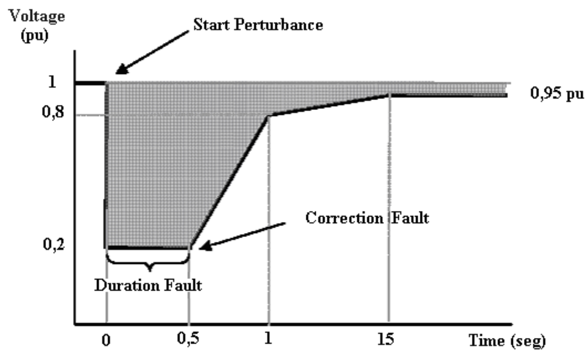

Fig. 1. Voltage – Acceptable Time at the Connection Point Curve

3. Support of the wind energy installations to the electrical network

According with the previous paragraph, one of the main objectives in the installations that produce wind energy is to adapt them in such a way that they give the maximum support to the electrical network at any given moment.

Currently, there are different technologies that try to reach this objective according to the characteristics and specific needs of each farm:

1) *Automatic Capacitor Banks*.
2) *SVC (Static Var Compensator) – TCR/TCSCl*
3) *STATCOM*
4) *Wind Turbine with Power Electronic Converter (DFIG)*

The research presented in this article is focused on incorporating automatic capacitor banks into wind farms, even though this methodology can also be applied to the other technologies mentioned by simply amplifying the algorithms according to the specific characteristics of the option elected. Likewise, though the data used in this study come from a concrete wind farm, there is no limitation concerning the characteristics and behaviors of any other installation that could be studied. Following this premise, a detailed analysis of the specific needs of a wind farm has been carried out, as well as a search for the optimum performance for the compensation of reactive power during peak time.

4. Study of the Needs and Description of the Farm

On the one hand, it is necessary to understand the characteristics and behavior of the farm in order to be able to define its necessities. Experimental data have been taken in the wind farm of Munilla (La Rioja, Spain), in order to carry out the study. This wind farm, property of Molinos del Cidacos Inc., consists of 18 wind turbines of 2.000 kW, with an installed power of 36 MW.

All of the measurements were taken over the course of several months between 2004-2005 with the aim of understanding the farm's different aspects of seasonal functioning due to wind variations.

Amongst the studies, the description of the farm using the PQ curve is included. From this curve we can understand the real necessities of reactive power that a wind farm presents constantly according to the amount of generated power [12]. As it is possible to see in Fig. 2, the necessities of reactive power have been analyzed with the purpose of being able to obtain, at any given time, the required values according to the RD 436/2004.

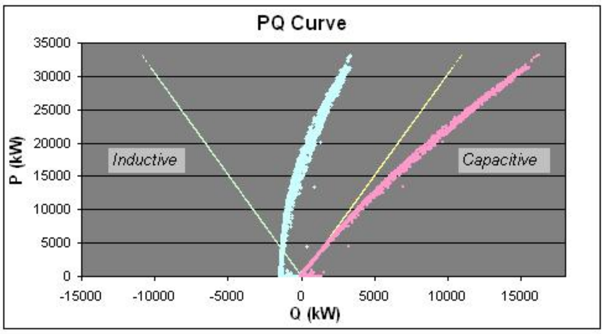

Fig. 2. PQ curve and requirements stipulated by RD 436/2004

An approximation of the PQ curve using a third-degree polynomial (1) is made in order to be able to work efficiently with the data collected from the wind farm (Fig. 3). In this way, the implementation of the optimization algorithm that has been developed is easier and faster.

$$Q = 3 \cdot \mathrm{e}^{-11} \cdot \mathrm{P}^3 + 3 \cdot \mathrm{e}^{-06} \cdot \mathrm{P}^2 + 0.0091 \cdot \mathrm{P} - 1364.7 \quad (1)$$

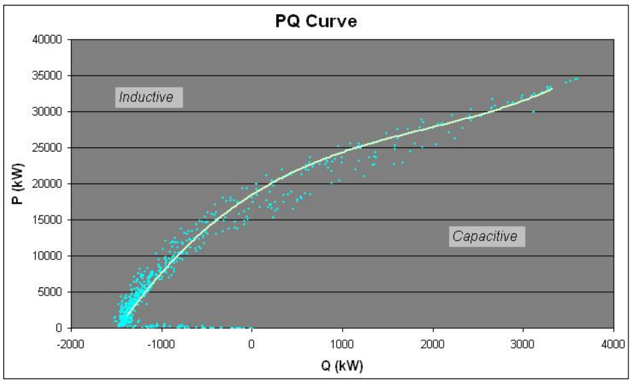

Fig. 3. Description of PQ curve at the Munilla wind farm

On the other hand, it is absolutely necessary to know not only the necessities of reactive energy but also the relative frecuency of the active power that is generated (Fig. 4), as well as of the reactive energy necessary for the compensation (Fig. 5). These data will serve as the base that will allow us to better optimize the capacitor banks according to the real function of this specific wind farm.

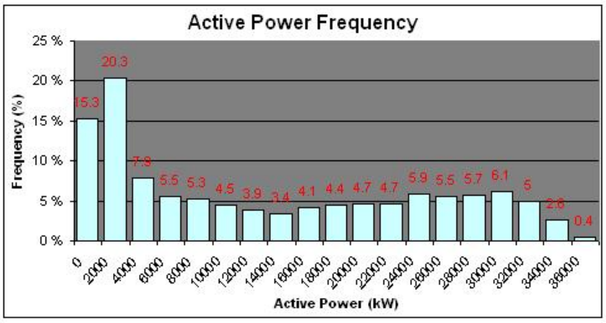

Fig. 4. Active Power Frequency generated by wind farm

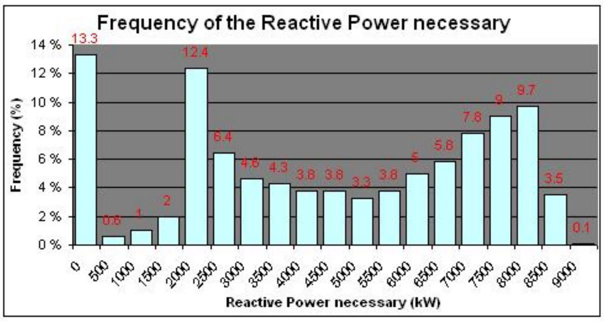

Fig. 5. Frequency of the reactive power necessary

5. Studies

With the aim of reaching the maximum degree of adjustment with the present legislation, RD 436/2004, the fundamental variables that have to be considered to optimize the value of the capacitor banks are the pay-off period of the installation and the benefits in 5 years. (Fig. 7 and Fig. 8).

$$Pay\_off = \frac{CapBankPrice}{(\sum_{i=0}^{N} f_i \cdot Bonus_i) \cdot AnnualProd \cdot ART \cdot \frac{4}{24}} \quad (2)$$

$$AnnualBenefit = (\sum_{i=0}^{N} f_i \cdot Bonus_i) \cdot AnnualProd \cdot ART \cdot \frac{4}{24} \quad (3)$$

$$Benefit5Years = AnnualBenefit \cdot (5 - pay\_off) \quad (4)$$

Where:

- CapBankPrice = Capacitor bank price in €.
- AnnualProd = Annual production of the wind farm in kW/h.
- ART = Average Reference Tariff in €/kW/h.
- f_i = relative frequency of production from fixed active power
- $Bonus_i$ = Bonus achieved from the fixed active power

An algorithm has been developed in Matlab with a Father-Son structure, In order to carry out this study, as shown below in Fig. 6:

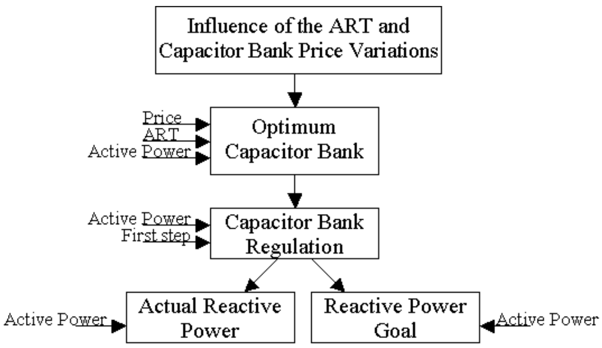

Fig. 6. Father-Son structure of the optimization algorithm

Using this algorithm, the problem of regulating the capacitor banks is independent of the problem of calculating the optimum value for the smallest capacitor unit. This is done in such a way that using diverse functions, which are aimed at the regulation of the steps of the capacitor banks, the same structure is maintained regardless of the configuration of the bank of capacitors. And on the basis of this common structure for the diverse configurations, the problem of the optimum value can be tacked according to the capacitor bank price and the Average Reference Tariff (ART). This structure also allows us to best study the influence of the variations of these two parameters: the capacitor bank price and ART.

A. Influence of the capacitor bank's configuration

The regulation of reactive power by means of capacitor banks is carried out using groups or steps. So, the optimum value of the diverse steps that compose the capacitor banks varies according to its configuration. The scenarios studied were the following ones:

- Configuration 1-1-1
- Configuration 1-2-4
- Configuration 1-2-2
- Configuration 1-2-2-4
- Configuration 1-1-2-2

Fig. 7 shows the pay-off period of the capacitor banks according to their configuration and the value of the principal step, or group. From the figure one infers, by default as well as by excess, that the configurations 1-1-1 and 1-2-2-4 respectively display a behavior different from that of the other configurations. In the case of type 1-1-1 the pay-off periods remain low except in the case of very small values in the principal group. This is basically due to the reduced benefits obtained from such a limited capacitor bank. Also, it is possible to be observed in Fig. 5 that the capacitor bank's frequency of use is reduced when presenting values between 500 and 1500 KVAr.

On the other hand, the type 1-2-2-4 shows some pay-off periods longer than those of the other configurations due the cost increase of the actual capacitor bank.

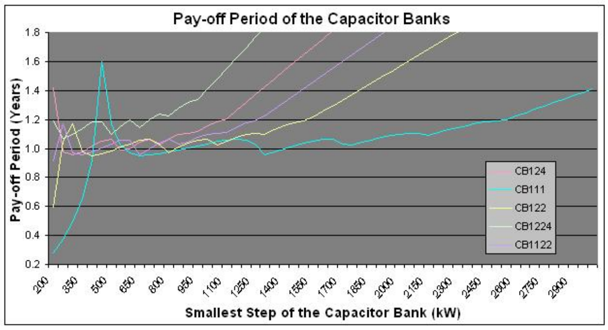

Fig. 7. Pay-off period according to the configuration of the capacitor banks

In Fig. 8 we can see the profit variations after 5 years relative to the configurations of the capacitor banks and the value of the main group. Note that the configuration type 1-2-2-4 produces a maximum profit lower than the other configurations, due to the excessive global value of the capacitor banks.

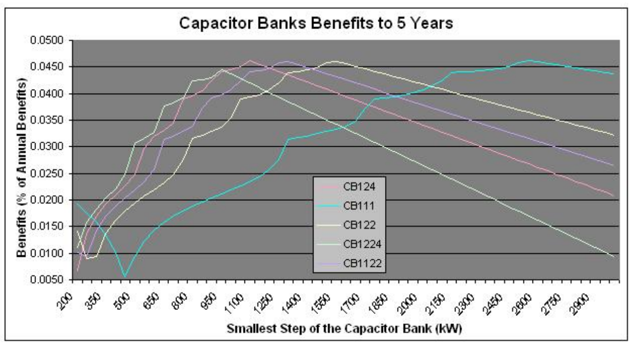

Fig. 8. Profit after 5 years according to the Configuration of the Capacitor Banks

B. Influence of the ART's variation

We have also carried out a study of the influence of the variation of the ART in the optimum value of the capacitor banks. As it can be seen in Fig. 9, the decrease of the ART involves a direct loss of profits, and even losses for very low values. As far as the optimum of the capacitor banks is concerned, it can be seen that for small values of the ART, the difference between the optimum value and other close values are not important. And a displacement of the optimum point toward lower values in the steps of the capacitor banks can also be produced.

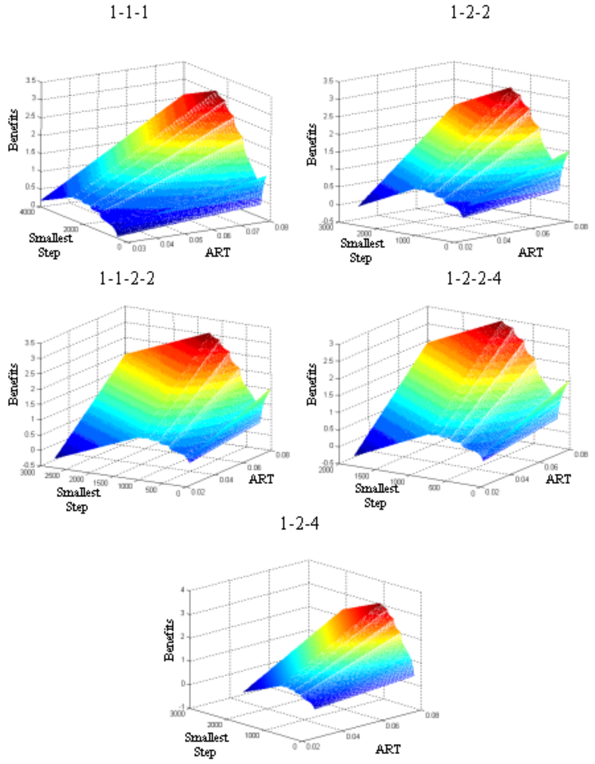

Fig. 9. Influence of the variation of the ART

C. Influence of the variation of the price of the capacitor banks

The same way that the value of the ART influenced the optimum point of the capacitor banks, the price of this capacitor banks directly affects that same point. Fig. 10 shows that when the price increases, the optimum point of operation decreases.

6. Analysis of Results

The compensation of the reactive energy that circulates through the network provides a better use of those networks, as well as to reduce the drops and the losses of tension. In this way it is possible to optimise the investment in the lines of transmission and distribution. The decrease of the tension drops and the improvement of the regulation of voltage is beneficial from the point of view of the stability of the network. In short, the compensation of the reactive energy circulating through the network is beneficial not only for that network, but also for the generation companies, both economically and functionally.

From the study carried out on the influence of the capacitor bank type on the optimum mode of operation we have concluded that the configuration 1-2-2-4 presents a lower profit across time in exchange for a greater capacity to regulate the reactive power during periods of high production. The rest of the configurations produce in each case similar benefits for their particular optimum operation point.

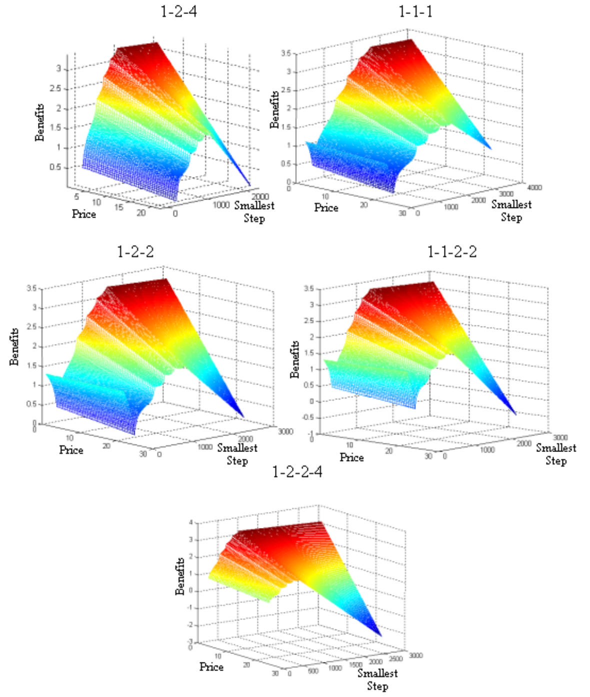

Fig. 10. Influence of the variation of the price of the capacitor Banks

From the remaining configurations we can see that 1-1-1 and the 1-1-2-2 demonstrate a greater work period outside of the performance range established by RD436/2004, such that they will not be able to compesnate for the installation up to the established values with a capacitive power factor of 0.95 in these periods.

7. Conclusions

The growing development of wind farms on a global scale brings with it the necessity to move ahead in the field of wave quality introduced into the electric network. This is so important that no longer wind farms are considered as mere passive elements, but their possibilities as elements helping the systems of transport and distribution are also taken in mind when they provide energy to these systems.

Even though doubly feed wind turbines show a certain capability in terms of modulating reactive power, the news requirements of reactive power regulation, similar to the requirements of conventional generation, in general, have made necessary to advance in systems of external compensation.

Within the possible options concerning the regulation of reactive power, we have studied the usage of capacitor banks. The work method employed has permitted us to perform, the calculation of the optimum value of the batteries independently on one hand, and the regulation of those batteries on the other hand. In this way it is possible to work with different configurations, while exclusively the algorithms that affect the operation of the capacitor banks are developed.

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