Improving the electrical value of Wind Power Plants

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Introduction

Wind power is going to play an important role in the electric generation in several countries. In EU the wind generation capacity exceeded 23 000 MW by the end of 2002 (with an annual growing in the year 2002 over 30%).

The integration of wind power in the power system is important in order to optimise the utilization of the resource and in order to continue the high rate of installation of generating capacity, which is necessary to achieve the goals of sustainability and security of supply through diversification of the power production, helping to reduce the dependency on imported fuels. Several phenomena can restrict the maximum capacity of wind farms that the grid can tolerate under a technical point of view; the thermal capacity of the feeder, the voltage level, the reactive power consumption and the power quality mainly in terms of flicker, harmonics and interharmonics.

Consider the combined system shown in the figure 1. In it, besides the wind generators, there are a system to control the reactive power, an energy storage system and a small size system (hybrid filter) to cancel the harmonics generated by the others systems, and to avoid the possibility of harmfull resonances with the grid.

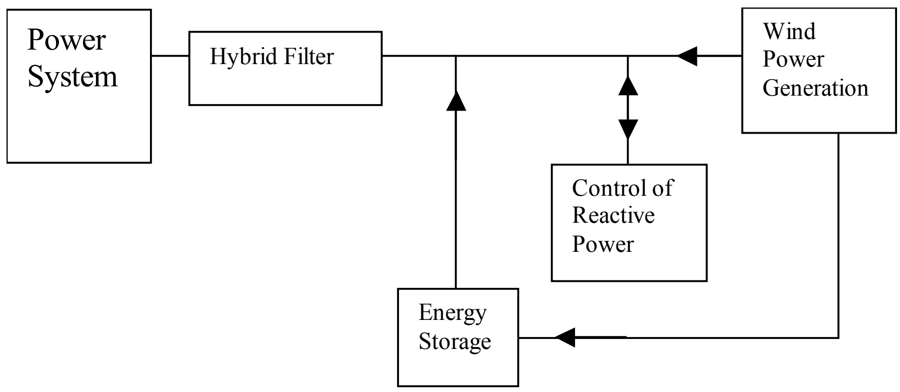

Fig. 1.: Block diagram of a combined wind generation system.

This combined system is highly flexible, offering the possibility to follow the desired strategy (control the voltage, follow the load, reduce the line losses), and inject a nearly constant active power, irrespective of the wind.

Voltage control

Operation of wind turbines may affect the steady-state voltage in the connected network and can result in voltages which may be above the statutory limits. The voltage fluctuations imposed by the wind farm will depend on the characteristics of the grid and the type of generator used [1].

The voltage level at the consumers is regulated by international standards, e.g. EN50160. Due to the impedance of the conductors the voltage level will change along the feeder depending on the wind power production and the consumer load.

Considering a general situation, some load can be connected in the point of common coupling of the wind farm. In the figure 2 the connection of a wind farm to the power system is shown, where R and X are, respectively, the resistance and reactance of short-circuit, and P and Q are the active and reactive power absorbed at the point of common coupling. E is the voltage of the ideal source in the Thevenin equivalent of the power system.

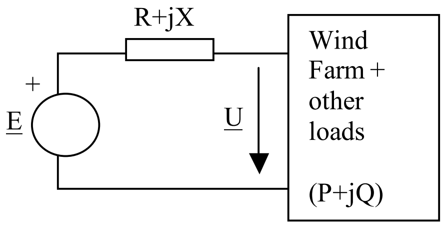

Fig. 2.: Thevenin equivalent of the agregated model

The variation of the voltage can be expressed as

$$\underline{\Delta U} = \underline{E} - \underline{U} = (R + jX)\underline{I} = (R + jX)\frac{P - jQ}{U} = \frac{RP + XQ}{U} + j\frac{XP - RQ}{U}$$

and the voltage at the PCC can be calculated by solving the following equation:

$$U^4 + \left[(XQ + PR) - E^2\right] \cdot U^2 + \left[(XP - QR)^2 + (XQ + PR)^2\right] = 0$$

As it is shown in these expressions, the voltage in the PCC is the result of the combination of several parameters and variables, as the active and reactive powers, and the characteristics of the network (equivalent resistance and reactance, that is to say, the module and angle of the equivalent impedance seen at the PCC).

The variations of the steady state voltage can be reduced controlling some of these parameters. It is clear that a reduction of the line impedance (R and X), moving the connection point closer to the source substation or reinforcing the existing distribution feeder for instance, would give less variations of voltage with the same power flow. Network upgrade and the construction of additional circuits is very expensive and it have significant environmental impacts.

In a general case, the wind farm can be connected at the PCC (generating active power P_g, and absorbing or injecting reactive power Q_g), in parallel with a load, characterized by its demand curve, (P_{load} and Q_{load}). We are going to consider also the possibility to have connected at the PCC a compensator (Q_{comp}) to control the reactive power injected into the grid, and an energy storage system in order to accumulate and release active power, $P_{storage}$. So, in the previous equations, $P = P_{load} + P_g + P_{storage}$ (positive values if absorbed; P_g is always negative), $Q = Q_{load} + Q_g + Q_{comp}$ (positive values if absorbed).

The figures 3 and 4 show that the voltage at the PCC varies with the total (net) active and reactive powers (The values are in per unit (note the unstable operation due to voltage collapse). Positive values of P and Q mean injected powers). The network impedance is 0.5 p.u., with an argument of 60 degrees, corresponding to a quite weak grid. The voltage of the ideal source, E, is considered to be 1 p.u. in figure number 3, and 0.9 p.u. in figure number 4.

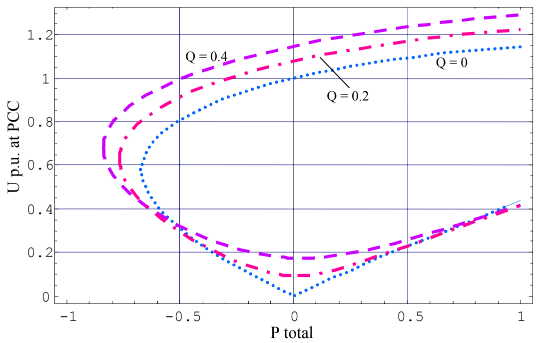

Fig. 3: Voltage (in p.u.) at PCC when E = 1 p.u.

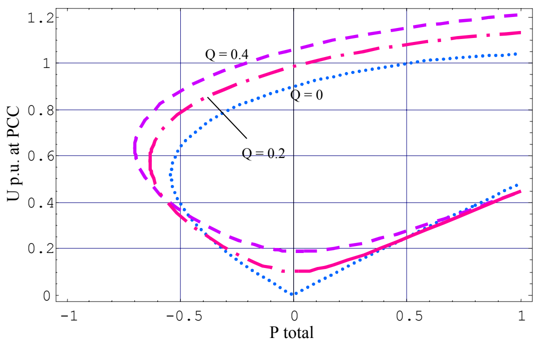

Fig. 4: Voltage (in p.u.) at PCC when E = 0.9 p.u.

The voltage falls as the power import is increased, and the rate of decrease of voltage accelerates at high loads. Injecting reactive power it is possible to bring the voltages at values near 1 per unit. With generation of active power (for instance, if the wind farm is alone), the voltage rise, but the increase can be reduced with importation of reactive power. In resume, the management of Q allows to adjust the voltage at the PCC at the required level.

Voltage stability (or, more correctly the risk of voltage collapse) in the steady state sense is an issue only for sections of network which are weakly connected to the rest of the system, and which have insufficient local generation feeding them. Additions of local generation (whether powered by wind turbines or by any other type of prime mover) should reduce power flows and mitigate the risk of voltage collapse [2].

The reactive power output can be automatically controlled in response to the voltage measured at the wind farm terminals or with a line drop compensation function for sites with tap change transformers, in order to control the voltage at some point on the network without having to measure there. These operation modes are already available at some wind turbine models. Reactive power can also be controlled as a function of output power or changed for different seasons or different times of day, either automatically or remotely by the operator of the system. The most flexible solution for the power system operator is to have remote control of the wind farm reactive power output.

Control of Active Power, P

Wind energy alone have spatial and short term stochastic variation. The generated power is dependent on the wind speed and wind speed fluctuations are reflected in uncontrollable output power variations. The wind speed regime also determines the availability of the output power of the wind turbines. the temporal variability imposes increased regulation capabilities on the rest of the generating system. The remaining conventional generation has not only to cope with load variations but also with variations in the power output of the wind turbines. Particularly a simultaneous wind speed decrease and load increase is problematic. The sudden loss of disperse generation due to excessively sensitive protections or power converters can lead to a jeopardising scenery.

The control of the active power can be made by controlling the power generation in the wind farm, or controlling the active power consumption at the PCC, (controllable loads or storage). The output power controllability is most important for short term balancing and the output power availability is most important for long term balancing. For short term balancing, the output power of a generator needs to be changed quickly but with small amounts. For long term balancing, the output power must be available when it is necessary to put it in operation.

- Constraining generation at critical times, eg reduction of P_g.

If voltage is found to be too high, the output of the generator must be reduced until an acceptable voltage level is reached. This marks a limit of allowable installed capacity. As wind power production occurs mostly below the rated (or installed) capacity, the adoption of the most disfavourable case lime is too severe.

Wind generation, particularly in large or transmission-connected projects, is likely to lose its 'must run' status, i.e. it will be subject to limitations by the system operators. At high wind penetrations, curtailment may be required because of limitations in the transmission system or limitations imposed by other generators.

A dynamic solution can be adopted, where the generation output is reduced only at critical times to maintain satisfactory voltages. This can be achieved by different ways, adjusting the wind turbine control setpoint or disconnecting individual wind turbines depending on the wind turbine control strategy. Curtailment has successfully been put into practice and shown to compare favourably with reinforcement. Other solution, the energy storage will be analysed later.

Reducing the output power is relatively easy and can be done in the following ways:

- When the turbines are grouped in a wind park, the wind turbines can be switched off one by one. The degree of controllability of the output power that is achieved in this way depends on the number and the rating of the turbines. Another drawback is the low response time to reconnect wind turbines.
- When variable speed wind turbines are used, the pitch angle of the blades can be increased, so that less than the maximum energy is extracted from the wind. This also cancels output power fluctuations for the largest part. With constant speed wind turbines, this is more difficult, because they are not always equipped with pitch control and because the rotating mass of the rotor can not be used as an energy buffer to smooth out wind speed variations.

- Increasing generation P_g.

Increasing the output power is more difficult, but also of more practical interest, because underfrequency occurs more often than overfrequency. In the figure 5, the characteristic curves of these are shown. The wind farm can be oversized compared to the network capacity if the power exported is constrained.

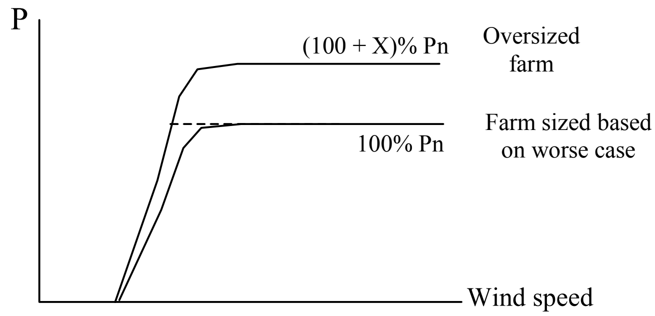

Fig. 5.: Wind farm power curve with and without power ouput limitation.

Compared to a 100% wind farm, the (100 + X)% wind farm will produce X % more energy during periods of low wind speed. At high wind speeds, the output of the wind farm is curtailed to 100%. However, the savings on grid reinforcement and the additional delivered energy at low wind speeds could be sufficient to produce better overall return on investment than the 100 % wind farm.

It has to be noted that all these solutions sacrifice energy yield in favour of controllability.

<u>- Load control.</u>
Demand side management. This is a dynamic solution where consumer load demands Pload and Qload are increased or decreased to reduce ΔV. There are flexible loads that can be switched on and off following the indications of the distributor. Other have the possibility to store thermal energy such as storage heater and hot water storage systems.

<u>- Energy storage.</u>
The problem of variable and unpredictable supply from renewable sources would be solved with the development of good energy storage systems. It can provide with some firm capacity, besides of giving more flexibility to follow the demand or the requirements of the system's operator, with the strategy more convenient in each moment (voltage control, reduction of power losses, constrain the production, rise the instantaneously production, etc.).

It consists on an intermediate stage between energy production and its consumption. Energy storage reduces the generation export into the distribution system by diverting part of the output into a storage device. Unlike load control, the stored energy can be recovered in electrical form and does not require consumer participation. The stored energy can also be re-exported provided there is no voltage constraint, and it can thus be used to take advantage of fluctuating electricity market prices. By storing the power from renewable sources during off-peak periods and releasing it at on-peak times, coincident with periods of peak consumer demand, energy storage can transform this low-value, unscheduled power into schedulable, high-value products. Energy storage is also a flexible option to eliminate local power quality problems (flicker and voltage level) as well as making the wind power schedulable as conventional power plants [3].

Storage also permit to increase the potential wind energy produced form the wind resources. Suppose a wind farm of nominal Power P_n (kW) and with a number of equivalent hours NEH. The annual energy yield is of NEH * P_n (kWh). But due to the variability of wind, the production of the energy is not constant along the time.

With an energy storage system, although the total energy produced by the wind farm is the same, the energy put in the network will be lesser due to the losses in storing and releasing the energy. Therefore, we can consider the power put into the grid as a constant, and to characterize the wind farm with a lesser nominal power, P_s. Then, we can write, Energy = NEH * P_n - losses = 8760 * Ps.

As NEH have usually values of 3000 h or less, the firm power (guarantied) P_s would be less than P_n /3. So it is possible to install three times more wind power (and to generate three times more energy) and with better technical characteristics. Besides, the losses in the line would decrease with a constant generation, as they are proportional to the square of the intensity of the current (Joule effect).

The strategy of control could be: if the active power generated by the wind farm is bigger than P_s, inject P_s into the grid, and the rest of energy would be transferred to the energy storage system; if there is less production than P_s, transfer (P_s – P) from the energy storage system and the rest from the wind farm.

A method to reduce the capacity of the energy storage system would be to accept some variations in the P injected into the grid (and accept some periods without injection) adopting a band, as shown in the figure.

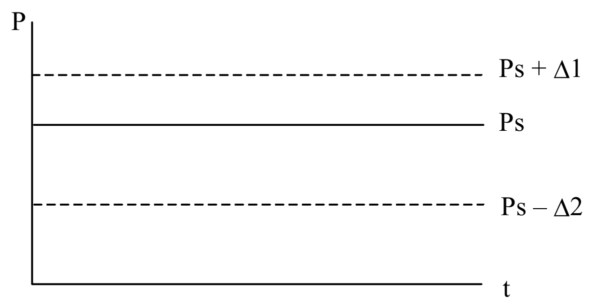

Fig. 6.: Bands for exported power for a simple control algoritm.

If the active power generated by the wind farm is bigger than $P_s + \Delta_1$, inject $P_s + \Delta_1$ into the grid, and the rest of energy would be transferred to the energy storage system; if there is less production than $P_s - \Delta_2$, transfer the difference from the energy storage system. With an adequate management of reactive power, it is possible to have a band in P, without impact on the voltage grid.

Nowadays, storage is uncommonly employed, mainly due to its high cost. New technologies as redox-flow technology and hydrogen generation can change this fact.

Benefits of Combined systems.

The system shown in the figure 1 offers a capacity credit (P_s) (defined as the amount of installed conventional capacity that can be replaced by the additionally integrated wind power generation plants without reducing the reliability of the overall supply system).

Without the storage, as available wind energy varies over time, capacity credit changes as well. Therefore the capacity credit in time of peak demand is generally used for further interpretation. Consequently, a high correlation between wind energy production and electricity demand would result in a high capacity credit assigned to wind generators. In some studies, for conservatism, wind generation is considered not to provide any capacity credit. It is clear that with energy storage there is an improvement of the capacity credit. This can also ameliorate the burden in the control of conventional generation units due to wind variability. The combined system proposed can offer some ancillary services (functions provided by generators in addition to energy production) [4].

The small hybrid filter provides with a high power quality, without problems related with harmonics, interharmonics, and flicker, avoiding the possibilities of harmful resonances [5, 6].

Obviusly, accurate wind forecasts are very important, because they would permit the optimization (and reduction) in the size of the different subsystems considered, specially the energy storage system.

Conclusions

In the present paper a combined system, consisting in a wind energy generator, a system to control the reactive power, an energy storage system and a small size hybrid filter to cancel the distortions and to avoid the possibilities of resonances is presented. The flexibility of the systems offers some capacity credit, giving a high operation cost value, high loss reduction value, a high grid investment value, and permits the installation of more wind capacity at the PCC, and hence, more wind energy production.

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Summary

In a wind farm, electrical power can be generated with a great environmental value, but some electrical characteristics are different from those of other classical power plants. Important characteristics of a power plant are the controlability of the output power, the availability of the power, the capacity of control of the voltage, the reactive power control, the contribution to the losses reduction in the power system, the increase of the reliability of the power system and capacity credit, the power quality improvement and the grid investment value.

The operation of a wind turbine installation may affect the steady-state voltage in the connected network. The voltage fluctuations imposed by the wind turbine will depend on the characteristics of the grid. Fundamental reactive power compensation can be used for power factor improvement, reduction of losses, increase of the steady-state transmittable power, voltage regulation (at intermediate points of a transmission line, or/and at the end of a line and transient and dynamic-stability improvements (to increase the first swing stability margin and provide power oscillation damping). Harmonics and flicker must be controlled. Also, to ensure power supply reliability it is important to avoid overload of the different components in the system.

Some active power control can be obtained constraining generation at critical times. This implies some reduction of the active power generated and/or use energy storage. The stored energy can be re-exported when needed.

In the paper, all these important topics in the operation of wind farms are analyzed and some possibilities are evaluated in order to improve the electrical value of the wind energy.