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FACTS: Its Role in the Connection of Wind Power to Power Networks

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1. Introduction

Environmental and political worries for a sustainable development have encouraged the growth of electrical generation from renewable energies. Wind power generation of electricity is seen as one of the most practical options and with better relation cost-benefit inside the energetic matrix nowadays (Angeles-Camacho & Bañuelos-Ruedas, 2011). Nevertheless, given that some renewable resources like the speed of wind or the solar radiation are variable, so is generated electricity. Without an adequate compensation, the voltage in the point of connection and the neighboring nodes will fluctuate in function to variations of the renewable primary power resource used. This phenomenon can affect the stability of the system and compromise quality of the energy of the neighboring loads (Gallardo, 2009). Nowadays, the generation with renewable resources integrated to electrical systems covers a small part of the total demand of power. The major generation comes from other sources such as the hydraulics, nuclear and fossil fuels. If the wind penetration system is small, the synchronous conventional generation will determine dynamic behaviour of the system, for example nodal voltages are maintained inside its limits of operation for this centralized generation (Ackerman, 2005). Nevertheless, with the increase in capacity and the number of power plants that use renewable resources added to the electrical systems, these will replace power from conventional sources, in such a way that the contribution of these cannot be ignored and the control of the nodal voltages will not be possible using the traditional methods.

The modelling of the dynamic interaction between the wind farms and the electrical systems can provide valuable information. The analysis of dynamic power flows allows the study in the time domain frame of reference with steady-state models and dynamic models. The simulation of the power network will allow analyzing the effects of the plants proposed depending on the time. The evaluation of the parameters of the network in the time will make it possible to see the complete range of his parameters with any injection of active power of the wind power station. Because of the need to deliver low energy parameters regulated by country, in recent years power electronics devices (FACTS) have been developed, which allow interconnection of different energy sources, including those of random behaviour such as wind turbines, on the same network supply (Angeles-Camacho, 2005).

2. Why power electronics?

Power electronics deals with the processing of electrical energy. Power electronics is an enabling technology, providing the need for interface between the electrical source and the electrical load. The electrical source and the electrical load can, and often do, differ in frequency, voltage amplitudes and the number of phases. Power electronics involves the interaction of three elements: copper, which conducts electric current; iron, which conducts magnetic flux; and, in prime position, silicon (Mohan et al., 2003).
The field is one of growing importance: it is estimated that over half the electrical energy generated is processed by power electronics before its final consumption, a proportion that is likely to reach 90% during the next decades.

2.1 Benefits

- To convert electrical energy from one form to another, facilitating its regulation and control
- To achieve high conversion efficiency and therefore low loss
- To minimize the mass of power converters and the equipment (such as motors) that they drive.
- Intelligent use of power electronics will allow consumption of electricity to be reduced

Two kinds of emerging power electronics applications in power systems are already well defined:

a. Bulk active and reactive power control
b. Power quality improvement (Angeles-Camacho, 2005)

The first application area is known as FACTS, where the latest power electronic devices and methods are used to electronically control high-voltage side of the network (Anderson & Fouad, 1994). The second application area is custom power, which focuses on low voltage distribution and is a technology created in response to reports of poor power quality and reliability of supply, affecting factories, offices and homes. It is expected that when widespread deployment of the power electronics technology takes place, the end-user will see tighter voltage regulation, minimum power interruptions, low harmonic voltages, and acceptance of rapidly fluctuating and other non-linear loads in the vicinity (Conseil International des Grands Réseaux Électriques [CIGRE], 2000).
Power electronics is a ubiquitous technology which has affected every aspect of electrical power networks, not just transmission but also generation, distribution and utilization. Deregulated markets are imposing further demands on generating plants, increasing their wear and tear and the likelihood of generator instabilities of various kinds. To help to alleviate such problems, power electronic controllers have been developed to enable generators to operate more reliably in the new market place.
Power electronics circuits using conventional thyristors have been widely used in power transmission applications since the early seventies (IEEE Power Engineering Society [IEEE-PES], 1196). More recently, fast acting series compensators using thyristors have been used to vary the electrical length of key transmission lines, with almost no delay, instead of classical series capacitors, which are mechanically controlled.

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3. Flexible alternating-current transmission systems

Power electronics form the basics of one devices family called FACTS, which offers a faster response times and lower maintenance costs compared to conventional electromechanical technology (Hingorani & Gyugyi, 2000). The FACTS concept is based on the incorporation of power electronic devices and methods into the high-voltage side of the network, to make it electronically controllable. FACTS controllers build on many advances achieved in high-current, high-power semiconductor device technology, control and signals conditioning (Acha et al., 2004). The power networks have limits that define the maximum electrical power that can be transmitted. Angular stability, voltage magnitude, thermal limits, transient stability, and dynamic stability are some of these limits (Song & Johns, 1999), and any violations of these limits can cause damage to transmission lines and/or electric equipment. These limits have been relieved traditionally by the addition of new transmission and generations facilities, but FACTS controllers can enable the same objective to be met without major changes to the system layout. Figure 1 illustrates the active power compensation achieved by different kinds of FACTS devices.

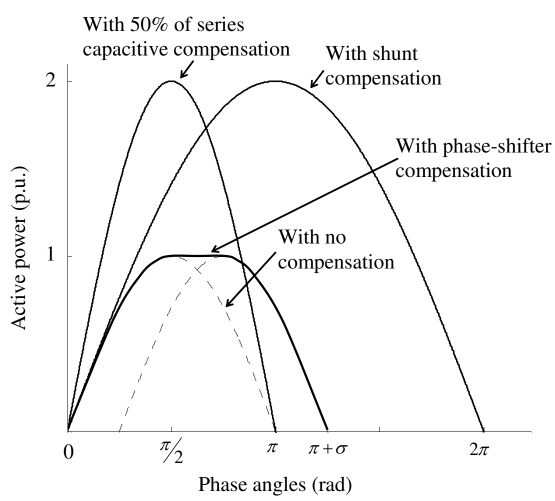

Fig. 1. Active power transmission characteristic for different types of compensation

The new reality of making the power network electronically controllable, has began to alter the thinking and procedures that go into the planning and operation of transmission and distribution networks in the world.

From the operational point of view FACTS introduces additional degrees of freedom to control power flow over desired transmission routes, enabling secure loadings of transmission lines up to their thermal capacities. They also provide a more effective utilization of available generation and prevent outages from spreading to wider areas. A three-bus network is employed to illustrate the use of FACTS to active power flow control.

The new reality of making the power network electronically controllable, has began to alter the thinking and procedures that go into the planning and operation of transmission and distribution networks in many parts of the world. The potential benefits brought about by FACTS controllers include reduction of operation and transmission investment cost, increased system security and reliability, increase power transfer capabilities, an over enhancement of the quality of the electric energy delivered to customers, and environmental benefits gained by increased asset utilization, Figure 2 shows active and reactive compensation achieved by different kinds of FACTS controllers (CIGRE, 2000).

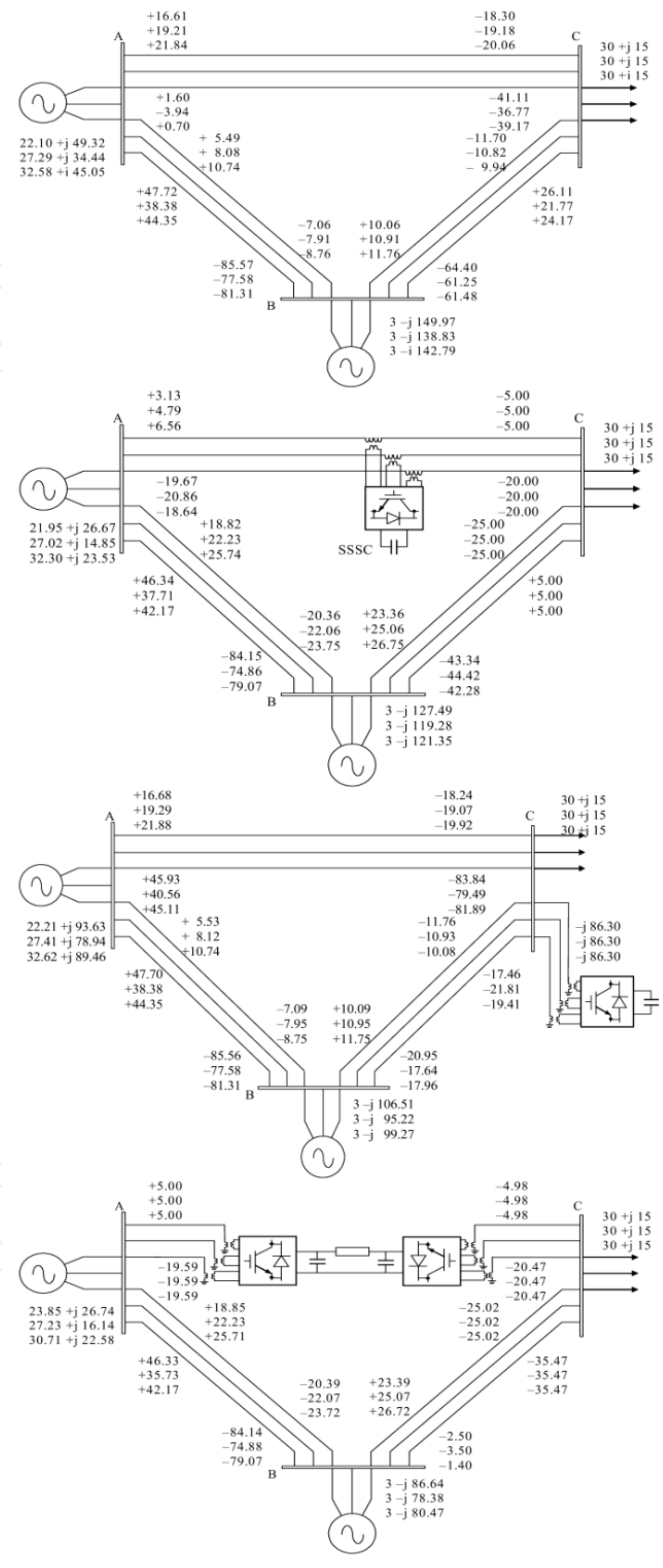

Fig. 2. Active and reactive power flows for different kind of power control: a) without compensation, b) phase shift control, c)shunt compensation, d) DC link.

Since FACTS devices are able to respond quickly to voltage fluctuations and provide dynamic reactive power compensation, there is mounting evidence that they would be very successful when considering the effects of a varying source of energy, such as wind generation, on a network.

4. Wind generation

An interconnected power system is a complex enterprise that may be subdivided into four main components: generation, transmission, distribution and utilization. The source of the mechanical power, commonly known as the prime mover, may be hydraulic turbines, steam turbines whose energy comes from the burning of coal, gas and nuclear fuel, gas turbines, or occasionally internal combustion engines burning oil.

Interest in renewable energy started in earnest in the early 1980s following the oil crises of the 1970s, when issues of security and diversity of energy supply and, to a lesser extent, long-term sustainability became apparent. Wind power generation became one of the most cost-effective and now is commercially competitive with new coal and gas power plants.

The wind resource is often best in remote locations, making it difficult to connect wind farms to the high-voltage transmission systems. Instead, connection is often made to the distribution system. The inclusion of a fluctuating power source like wind energy distributed throughout an electrical grid affects the control of the grid and the delivery of the stable power. The introduction of large amounts of wind power into the grid increases the short-term variability of the load as seen by the traditional generator, thus increasing the need for spinning reserve. It also changes the long-term means load as winds change, disrupting the planning for bringing generation on lines (Song & Johns, 1999).

Wind power grid penetration is defined as the ratio of the installed power to the maximum grid-connected load. Presently, Denmark has the highest grid penetration of wind at 19%. It has been suggested that with additional technology, 50% grid penetration will be feasible. For instance, in the morning hours of 8 November 2009, wind energy produced covered more than half the electricity demand in Spain, setting a new record, and without problems for the network (Manwell et al, 2002).

Induction generators are often used in wind turbines applications, since they are robust, reliable and efficient. They are also cost-effective due to the fact that they can be mass-produced. In the case of large wind turbines or weak grids, compensation capacitors are often added to generate the induction generator magnetizing current. Furthermore, extra compensation (such as a power electronic system) is added to compensate for the demand of the induction generator for reactive power. Some typical configurations of wind turbines connections are shown in Figure 3.

5. Grid integration technical problems

There exist a number of barriers which slow down the wind power exploitation. As the interconnection of wind power involves a number of technical problems different challenges need to be addressed. The assessment of the technical impacts of an installation must be accomplished, including,

- Transient Stability
- Voltage Control
- Frequency control

- Short Circuit Currents
- Power Quality Issues

The impact and consequently the level of penetration for power system network is an important issue. Methodologies and tools to overcome the technical problems need to be addressing the issue for increasing the wind power connection large–scale power system (Diaz-Guerra, 2007).

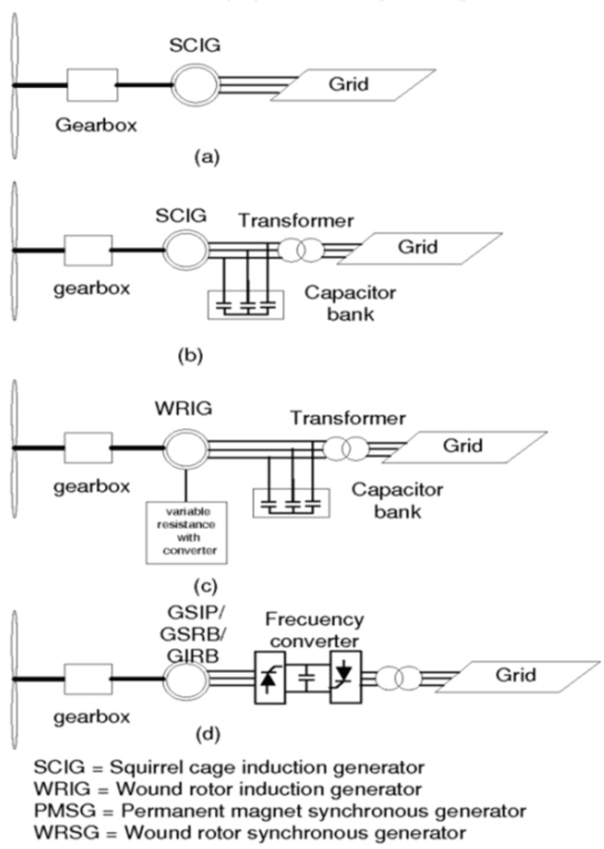

Fig. 3. Typical wind turbines connections.

Transient Stability, traditional generators attempt to follow the fluctuating load in order to minimize voltage and frequency fluctuations. During fault (voltage depression) generators accelerates due to the imbalance between mechanical and electrical powers. When the fault is cleared they absorb reactive power depressing the network voltage, if not enough reactive power is supplied a voltage collapse is eminent. Synchronous generator exciters increase reactive power output during low voltages and thus support voltage recovery, In contrast induction generators tend to impede voltage recovery. If the penetration of wind generation is high and they disconnect at small voltage reductions it can lead to a large generation deficit, to prevent this wind parks are required to have adequate compensation (Fault Ride Through Capability).

Voltage Control, Nodal voltages in power systems are normally allowed to fluctuate from ±5% to up to ±7%. Synchronous generator and other compensator devices regulate nodal voltage by supplying or absorbing reactive power. In contrast induction generators absorb reactive power and have no direct control over reactive power flows. Even variable-speed wind turbines may not be able to control the voltage at the point of connection, because the wind farm network is predominantly capacitive.

Frequency control, Frequency in large electric grids is maintained at ±0.1% of the desired value, in order to have frequency control, generator power must increase or decrease. Wind generators respond to frequency changes by adjusting either, in fixed-speed the pitch angle or in variable-speed by operating it away from the maximum power extraction curve. In any case, thus leaving a margin for frequency control in wind generation.
Short-Circuits Currents, The induction wind generators, contribute to the short-circuit current only in the instant of appearance of the fault. In contrast, during voltage depression a large short-current is needed, synchronous generators contribute "many times" their nominal current. With high penetration levels the risk of disconnections by voltage depression will increase.
Power Quality Issues, voltage harmonic distortion and flicker are the principal quality effects of wind power generation. The injection of harmonics into the power system is the main drawback associated with variable speed turbines because these contain power electronics. Voltages fluctuations (flicker) are produced by the variability of the power generated in fixed-speed wind turbines.

6. Wind farm model

One of the tools most used in the electric systems planning and design is the analysis of power flows; a variant of this tool is the analysis of Dynamic Power Flows. Investors and companies execute the necessary preliminary studies.
The analysis will allow us to evaluate the effects of the plant proposed over the network to be incorporate. However, models to perform the power flow analysis and understand the dynamic interaction between the wind farms and the electric systems must be developed.
A basic model of a wind farm consists of four parts, the simulator of wind speed, the wind turbine with the gear box, the generator with its individual (optional) compensation and the electrical network to which it will be interconnected (Diaz-Guerra, 2007). In the case of not having compensation it will deliver the active power and will take of the network the reactive power, (Figure 3a), where there appears a wind generator of induction connected directly to the electrical.
The present work makes use of a wind farm model based on several wind generators as the scheme presented in the Figure 4, where an induction generator is connected to the network and compensation is supplied in order to supply the requirements of the generator´s reactive power. The bank of capacitor provides an affixed amount of reactive power locally, so that it does not have to be imported from other parts of the grid. It is assumed that the site being considered for a wind farm is comprised of 12 wind turbines rated 2500 kW each.
The goal of the model is to calculate the active power provided by the wind generator, given the measured values of wind speed and his direction (Feijoo & Cidras, 2001), as well as the reactive power, which depend on the active power and the voltage of connection. The active power produced by a turbine can be expressed by the following equation:

$$P = \tfrac{1}{2}\rho A v^3 C_p \tag{1}$$

where P is the real power in Watts, ρ is air density in kg/m^3, A is the rotor area in m^2, and C_p is the power coefficient.

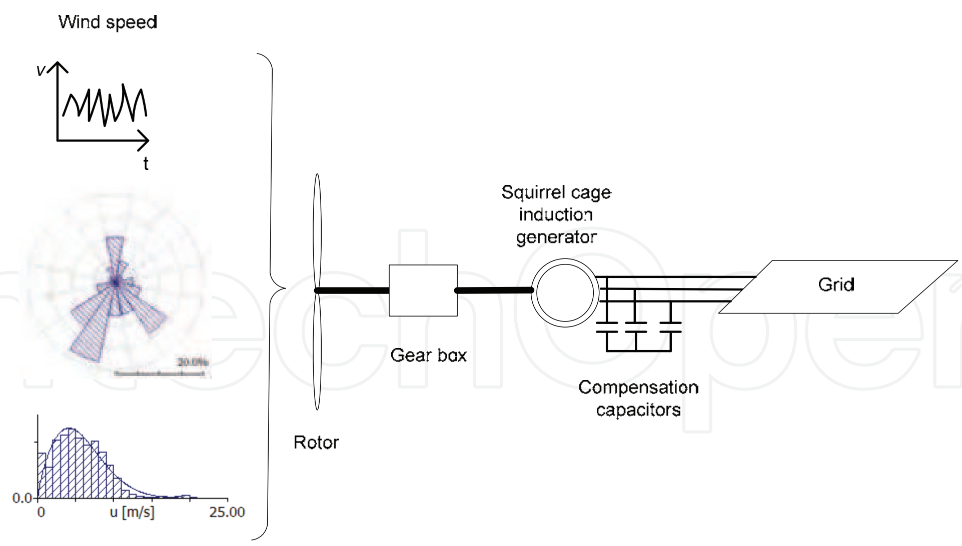

Fig. 4. Grid coupled wind generator.

6.1 Active power

To show the relation between the active power produced and the wind speed, one month of 28 days (February 2008) real data for a specific site in the Mexican state of Zacatecas is used for the wind model; data points for speed are at 10 minutes interval (4,032 points). The data points are connected to get a wind speed curve, seen in the upper plot of Figure 5. The real power produced by each wind turbine is calculated using equation 1. The contributions of the twelve individual turbines are summed at each 10 minute intervals to derive the total real power curve for the wind farm. Figure 5 shows the wind speed (top) and the real power (bottom) produced by a wind farm.

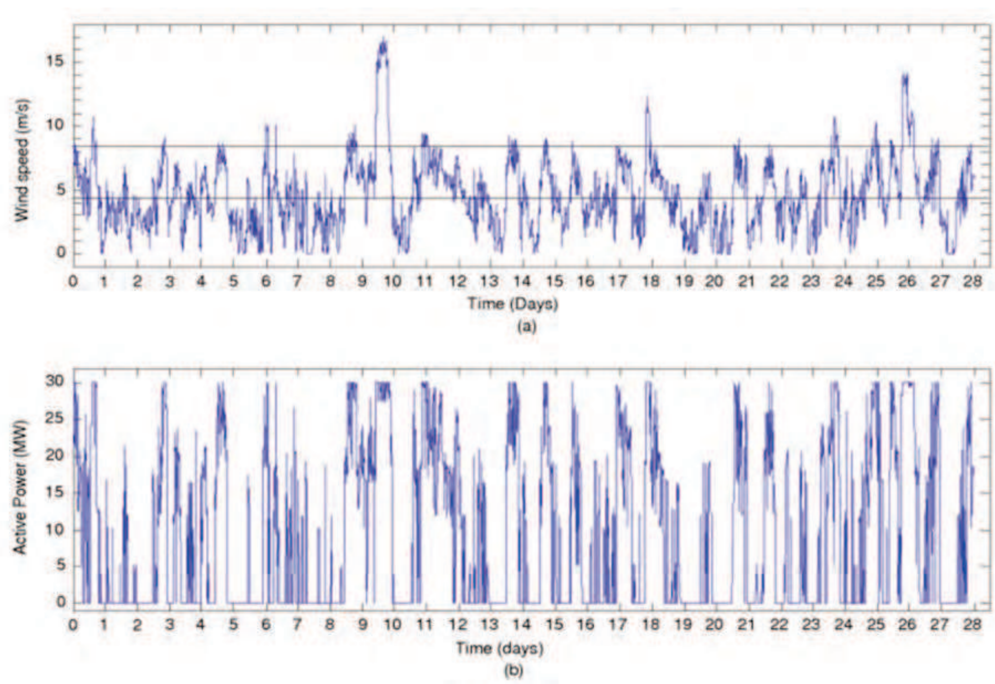

Fig. 5. Wind speed (a) and the real power produced (b) by a wind farm.

The cut-in speed is a conventional one of 4.5 m/s, it cab observed as producing no real power below it. Rated wind speed is 8.5 m/s, when it is surpassed; the active power curve flattens out at 30 MW. The cut-out wind speed of 24 m/s is not reached in this time period.

6.2 Reactive power

Reactive power can be calculated using the steady-state model of the induction machine and applying the Boucherot´s theorem (Feijoo & Cidras, 2001),

$$Q = \frac{V^2\left(X_c - X_m\right)}{X_c X_m} + \frac{X\left(V^2 - 2RP\right) - X\left[\left(V^2 - 2RP\right)^2 - 4P^2\left(R^2 + X^2\right)\right]^{\frac{1}{2}}}{2R^2 + 2X^2} \tag{2}$$

where V is the voltage, P is the real power, X is the sum of the stator and rotor reactances, X_c is the reactance of the capacitor bank, X_m is the magnetizing reactance, and R is the sum of the stator an rotor resistances. Both active and reactive powers are knows and the generator can be modeled as a PQ bus for power flow analyses and dynamic power flow analysis. The generator requires proportionally more reactive power at higher real power outputs. Figure 6 shows the relationship between active power production and reactive power absorption (top) and the respective reactive power absorption for the PQ model. The wind farm is modeled as being situated in Zacatecas, México. Wind speed actual data for the month of February 2008 is used.

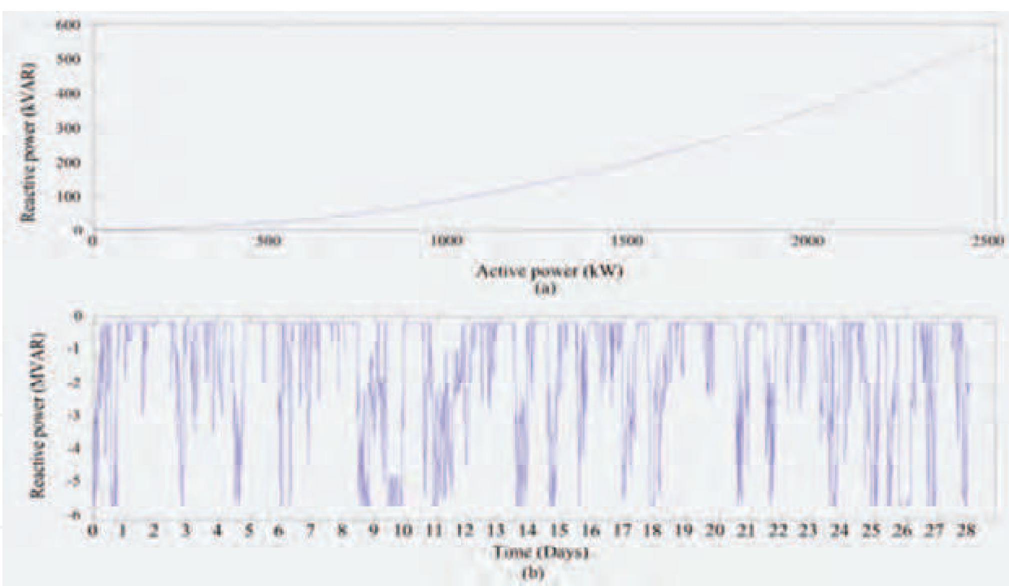

Fig. 6. Relationship between active and reactive power (a) and reactive power generated in function of wind speed and nodal voltage (b).

7. Wind integration study case: FACTS role

Digital software for analysis and control of large-scale power networks under both balanced or unbalanced conditions was developed. The software was written in Visual C++ with the philosophy "Object Oriented Programming (OOP)". The three-phase OOP power flow program has been applied to the analysis of a large number of multi phase power networks, of different sizes and complexity. Power flow solutions converge in five iterations or less to a tolerance of $1e^{-12}$, starting from a flat voltage profile. The accuracies of the solution have been tested again with commercial software and single-phase program (Angeles – Camacho, 2005).

7.1 Power flow case study

A small traditional network (Acha et al, 2005) shown in Figure 7 is used as the basis for illustrating how the PQ wind farm model works for two kinds of power analysis tools, firstly a power flow analysis is performed and secondly a dynamic power flow analysis is carried out. This is a five-bus network containing two generator, four loads and seven transmission lines. Figure 7, shows the test network used in the study with two particular solutions, (a) with zero wind power and (b) with maximum wind power (30 MW) which represents 15% of wind penetration. The Newton-Raphson power flow program takes a maximum of six iterations to reach convergence at each of the 4,032 data points.

Nodal voltages	Wind power	Nodes at network					
		North	South	Lake	Main	Elm	Wind
Magnitude (p.u.)	Without	1.06	1.0	0.987	0.984	0.972	0.979
	Maximum	1.06	1.0	0.989	0.986	0.973	0.982
Phase Angle (degrees)	Whitout	0	-2.06	-4.64	-4.96	-5.77	-5.39
	Maximum	0	-1.25	-3.42	-3.51	-3.97	-2.60

Table 1. Voltage of five-node network for zero and maximum wind power generation

It can be observed from the results presented in Figure 7 and Table 1 that all nodal voltages are within accepted voltage magnitude limits, i.e. 100 ± 6% in the UK in both cases, minimum and maximum wind power injections. At minimum wind power the largest power flow takes place in the transmission line connecting the two generator buses: 89.3 MW leave North. This is also the transmission line that incurs higher active power loss, i.e. 2.5 MW. The active power system loss is 6.12 MW per phase, this represents the 3.57 % of the active power generation. In maximum wind power injection the line is unloaded to 66.5 MW in general must lines are unloaded and losses are reduced to 4.66 MW. However, lines connecting Main-Wind changes the flow direction of power to wind-main. The new transmission line Main-Wind will reverse the active power flowing from Main towards Wind originally at 6.60 MW to a new flow towards Main at 10 .72 MW. Whereas the transmission line connecting Wind to Elm increases the active power flow from 6.58 MW to 19.28 MW, it means an increase of almost two hundred percent.

7.2 Dynamic power flows

A general dynamic power flow algorithm using an implicit trapezoidal integration method with Newton-Raphson iterative method has been developed and used (Burden & Fires, 2000). The algorithm takes advantage of the power flow used in the previous section. Ordinary differential equations describing the active power plant components and the algebraic equations corresponding to the active and reactive nodal power injections are now solved, simultaneously. There are 4,032 data points, for each data the software take five iterations to reach converge.

As expected, the nodal voltage magnitudes of all of the loads buses are affected by the variability condition of the primary source of power, the wind. They have high fluctuations.

Only bus slack (North) and PV bus (South) are not affected. They remain constant at 1.06 and 1.0 pu. The wind farm was modeled with a source of reactive power that is equal to 70% of the reactive power consumed by the generator at nominal voltage and its correspond active power produced by the wind speed data. Figure 8 shows the impact of the wind power produced in the voltage magnitude profile of nodal voltages of five-node network.

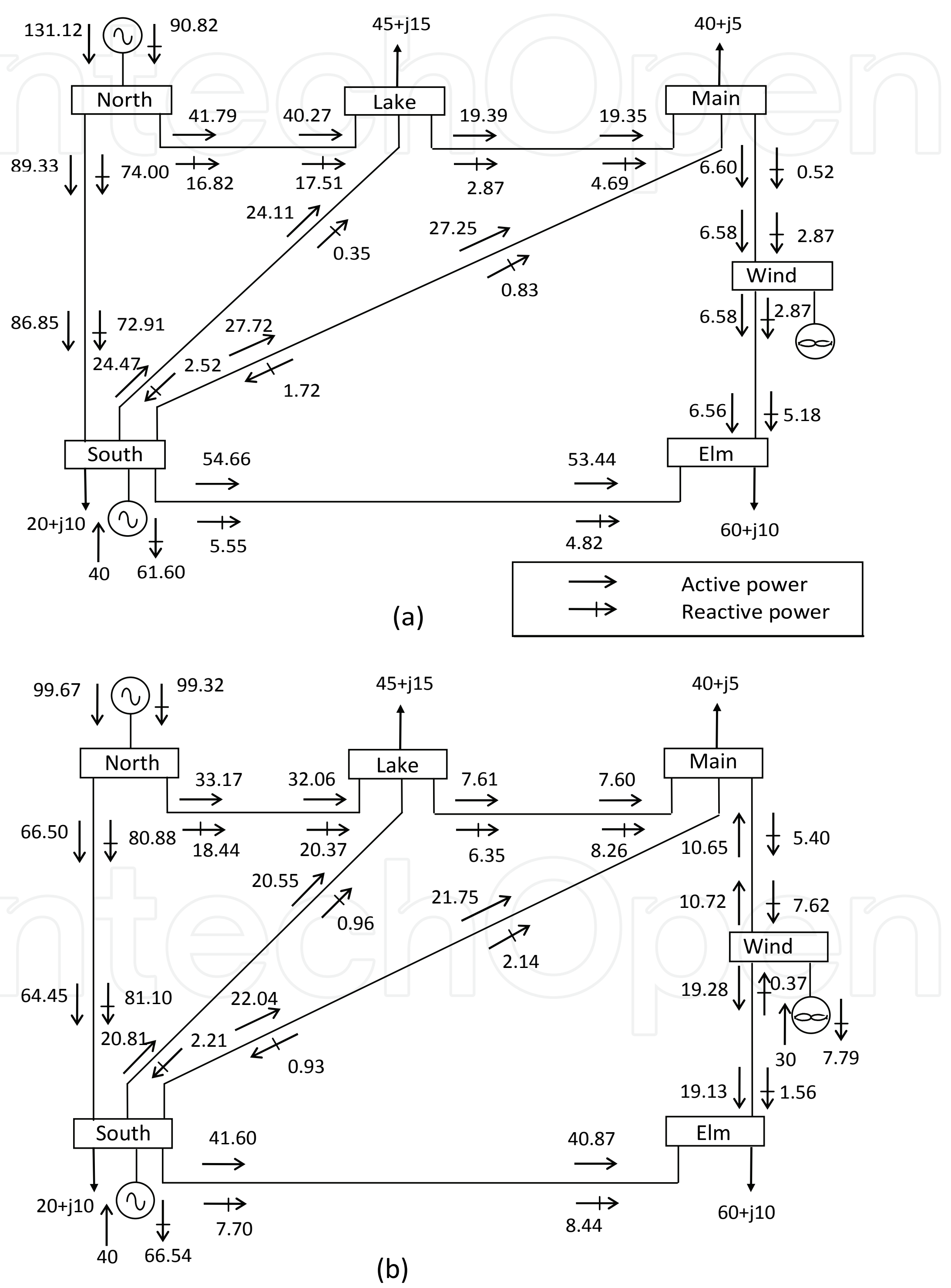

Fig. 7. Five-bus test network, (a) with zero, and (b) within maximum wind generation.

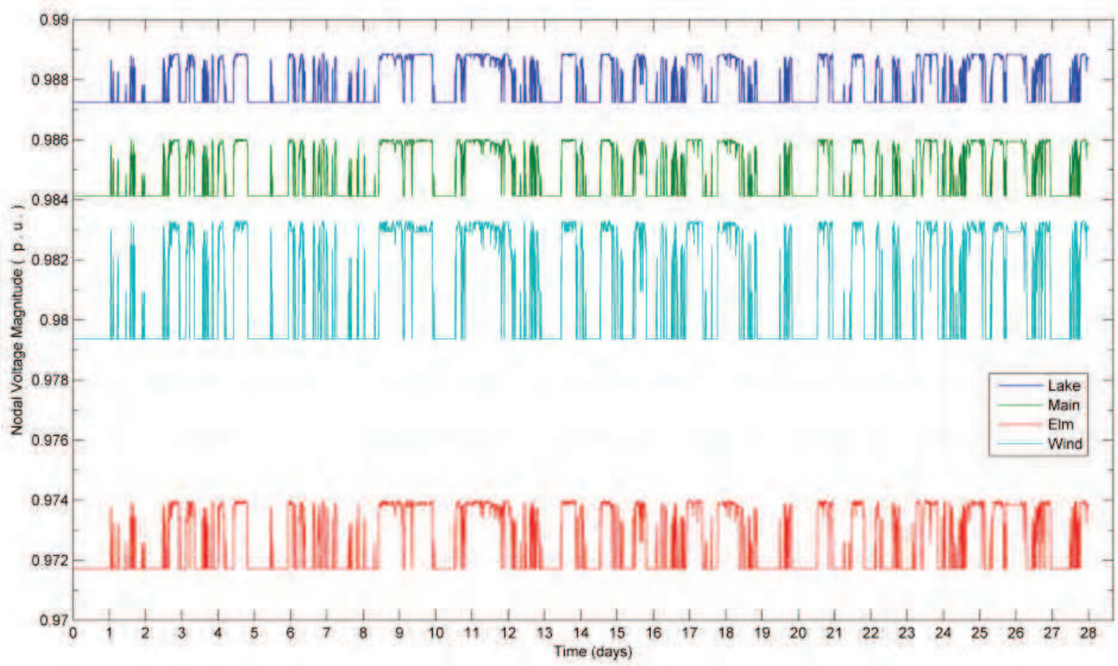

Fig. 8. Nodal voltages profile of five-node network with wind power generation.

Due to the high fluctuations of active and reactive power injection, transmission lines are under stress for short times. On the other hand transmission lines are now unloaded due to the fact that now active power is supplied locally rather than transmitted long distances. Figure 9 shows the transmission line active power flows. It is noticed that apart from flow reduction and flow fluctuation which do not seem to be significant, the transmission line connecting Main to Wind is under several reverse active power flows in short times, in power systems it is not a problem at all, however, at distribution levels, transmission lines trip can arise.

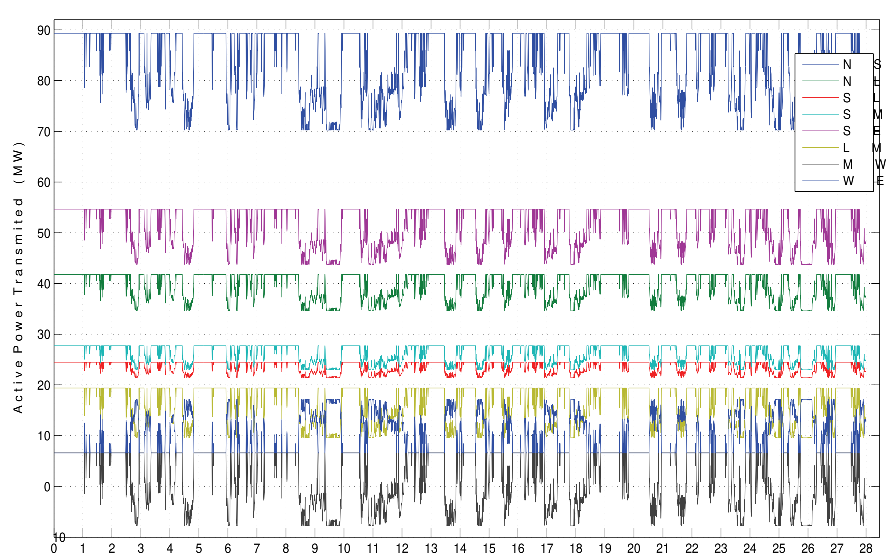

Fig. 9. Active power transmited over transmision lines.

8. Incorporation of FACTS into the dynamic power flow

As can be seen in the previous figures, power generation using wind resources creates voltages fluctuations in the networks due to the varying injection of real power and varying absorption of reactive power, exposing the network to voltage deviations. Dynamic reactive power compensation with FACTS controllers can potentially stabilize the voltage fluctuations associated with the wind farms and provide seamless grid interconnection. Also, the sensibility of the wind turbines to voltage trips can be improved. Dynamic reactive power compensation locally can allow the wind farm to remain operational during faulty conditions, this would avoid power unbalances or even systems collapse. FACTS technology offers an attractive option when considering the effects of a varying source of energy, such as wind and solar generation.
The static compensator (STATCOM) is a power system controller VSC based suitable to provide dynamic compensation to transmission system. Its speed of response enables increased transient stability margins, voltage support enhancements, and damping of low frequency oscillation. The voltage generated by the STATCOM is adjusted with little delay by virtue of semiconductor valves switching. The STATCOM can be seen as a ideal voltage regulator for long-term dynamic power flows. In other words magnitude voltage at the point connection is maintained at the set value in the face of voltage variations.
The five-bus network used is modified to include the STATCOM model (Angeles-Camacho & Barrios-Martinez, 2009). Using the software developed, a power flow analysis was carried out for the 4,032 data points. It is used to control voltage magnitude at Lake at one per unit. The objective of this simulation is to assess the capability of the controller to keep a constant voltage magnitude at the connecting bus. The power flow results indicate that the STATCOM generates 20.45 MVAR, in order to achieve the voltage magnitude target at minimums wind power injection. Nodal voltages profiles of five-node network with wind power generation and within the STATCOM embed are shown in Figure 9.

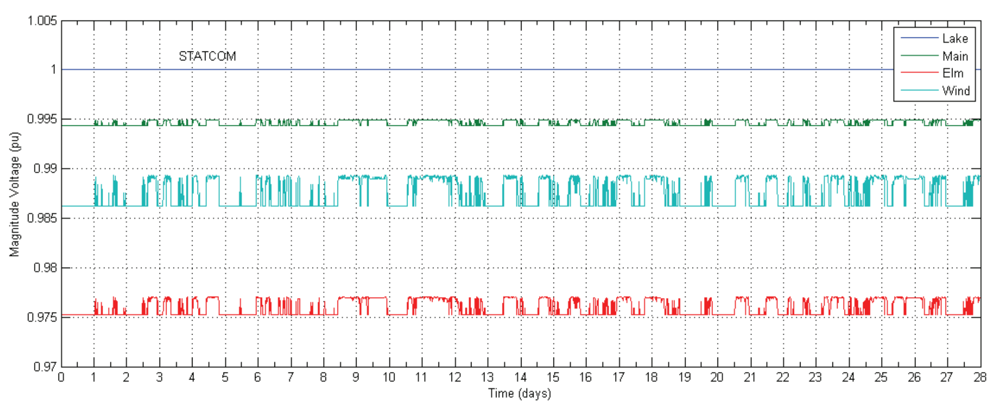

Fig. 10. Nodal voltages profiles of five-node network with wind power generation and within the STATCOM embed.

Analyses of Figure 9 show that significant changes occur in nodal voltage magnitudes when the STATCOM is present in the network compared with the case study where no STATCOM is included. For one the voltage magnitude in the STATCOM bus boosted by the STATCOM is maintained at its set value of one per unit. Keeping the voltage magnitude at the STATCOM bus at one per unit also flatted the remains nodal voltages.

8.1 Dynamic power flow case of study FACTS embedded

The dynamic power flow enables the study of different kinds of disturbances, which may occur at any point in time during simulation time. Among these are load increments/decrements, switching in and out of transmission lines, short-circuits faults, and loss of generation.

The five-bus network was used for testing the dynamic power flow algorithm. For the purpose of this test case, both generators were selected to be steam power plants. Gains and time constants were adjusted to maximize dynamic effects. Generating plants were assumed to be equipped with AVR, governor and a three-stage steam turbine. The dynamic response of the network was assessed by simulating major disturbance events and less severe events causing only voltage step changes of different magnitudes.

Using the software developed, a dynamic power flow analysis was carried out. This case study is a sudden reduction of three-phase power system load followed by a restoration to its normal level. The per phase load connected to bus Elm is disconnected and restored minutes later. It becomes apparent that any step load perturbations in power network loads have an effect on the outputs of all generating plants in the interconnected system. Power generation is altered by the regulatory action of the speed governor and turbine; hence, frequency and nodal voltages are deviated from schedule values. The remaining variables at each generator are also altered.

The objective of this simulation is to assess the capability of the controller to improve transient stability and avoid the wind generation being disconnected by voltage, frequency or load angle reduction after disturbs in the power network. If wind generation is disconnected can lead a large generation deficit. Figures 10 and 11 show the response of the generating plants to a step load disturbance for both cases (a) without compensation and (b) compensated.

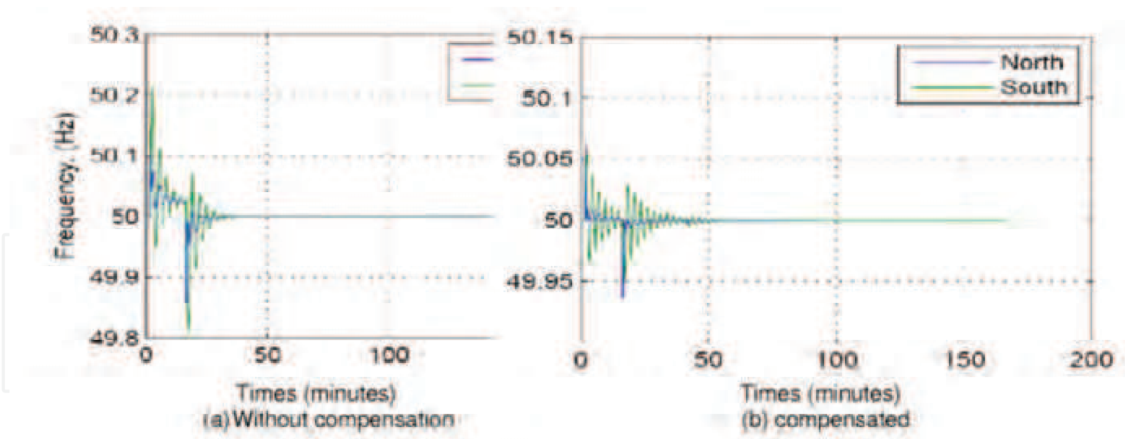

Fig. 11. Frequency generating plant response of the system; (a) without and (b) with STATCOM.

9. Conclusions

Today there is an increasing demand for planning the connection of renewable generation in details seen from the perspective of the electricity grid.

A large-scale penetration of renewable requires improvements in the infrastructure of the transmission network, both within a national electrical system and in the interconnections between countries, to balance variable power output and demand across regions and to transmit the renewable energy generated by non-conventional Renewable energies (NCRE) power stations.

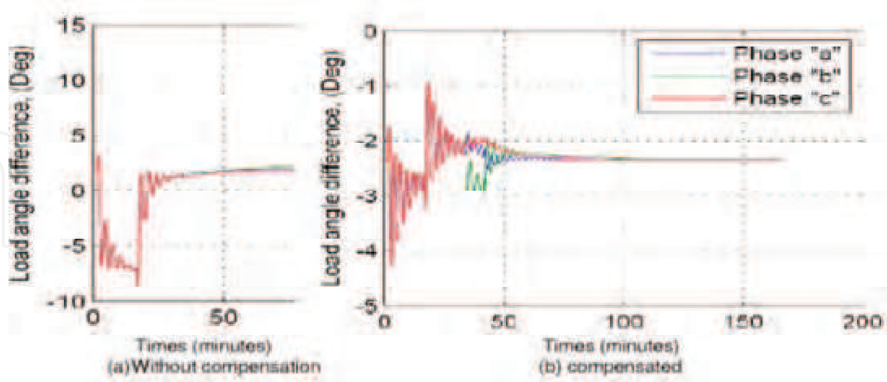

Fig. 12. Load angle generating plant response of the system; (a) without and (b) with STATCOM.

These are typical questions that have to be considered by the system operator before commissioning a power plant using renewable energies. Is there a risk of low voltage gradients due to changes of the renewable resource?; How would a black out of a wind farm affect the stability of the grid?; Can the wind farm run through a 3-phase-fault on the grid?.
Load flow analyses and dynamic studies have to be made in advance to analyze how the decentralized power production from renewable energies would affect the load flow conditions in the grids. This chapter focuses on using a wind farm model suitable for incorporation in both power flow analysis and dynamic power flow analysis. The chapter presents a set of case studies to illustrate the benefits that FACTS technologies bring to facilitate the connection of wind power to power systems.

10. Acknowledgment

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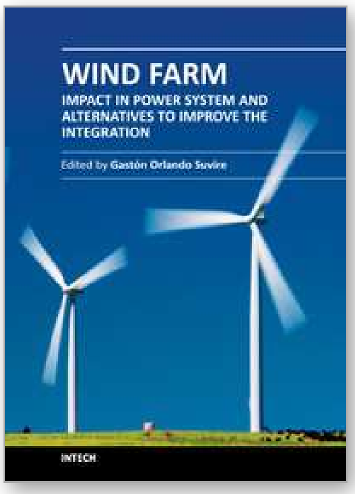

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