Simulation of FACTS for wind farm applications

A.Papantoniou and A.Coonick
Dept. of Electrical Eng., Imperial College
London SW7 2BT

INTRODUCTION

The simulation of FACTS (Flexible AC Transmission Systems) is essential in order to provide insight on the interaction of FACTS, wind farm(s) and the grid prior to any application of such systems. A typical wind farm - FACTS arrangement (Fig.1) is considered here. Two FACTS devices are utilised. Firstly a dump load sheds the extra power produced, or is activated during a wind farm cut out to prevent the isolated wind farm voltage to shoot up [1]. A UPFC is also considered which combines reactive power compensation (instead of an SVC [2]) and voltage control (instead of a TCSC [3]).

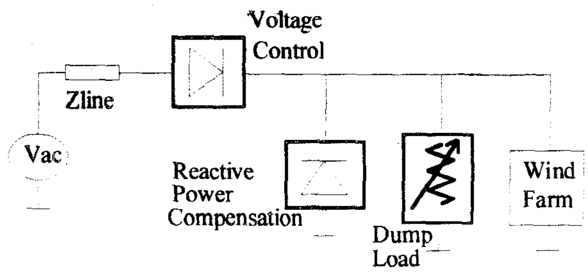

Figure 1: Wind farm - FACTS system

The wind farm considered here is comprised of 5 horizontal axis turbines, each having a capacity of 300kW (Fig.2). The 3 blade hub is coupled to a step up gear and through a coupling mechanism (usually fluid), to an induction generator. Not shown in the diagram is the pitch controller and the associated servo mechanism. Wind farm temporal and spatial dynamics as well as tower structural dynamics have also been considered [3].

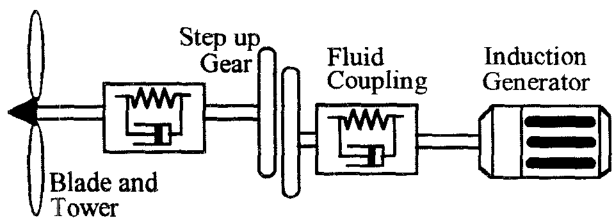

Figure 2: 300kW Wind Turbine block diagram

The overall system must be tested so that to ascertain its reliability in producing energy without adversely affecting the rest of the system. Thus, the following must be addressed:

1. The voltage profiles stay within statutory limits.
2. Reactive power requirements are limited.
3. Harmonics levels are acceptable.
4. When isolated, the wind turbine remains stable.

All the above indicate a requirement of both transient and frequency response analysis of the integral system. Furthermore, tests of the behaviour of the wind farm when isolated also indicate that a change in the system topology will be required.

Designing procedural programs (using a high level language such as FORTRAN or C) is not an attractive option. It involves linearisation of all equations, solution of all the differential equations and time stepping. The designer must design both the modelling tool and the simulation software. Furthermore, due to the conflict between the FACTS short time scales and the wind farm large inertia, variable time stepping software is required, otherwise the simulation would provide either inaccurate or incredibly slow solutions.

BEHAVIOURAL PROGRAMMING:

The alternative, is to use one of the available simulators (EMTP, SPICE, SABER etc). Most advanced simulators employ modelling tools based on **behavioural programming** instead of the traditional **procedural programming**.

Programming in a high level language is called **procedural** simply because if two equations are executed, precedence in the program flow is very important since interchanging the equations will give a different result.

With **behavioural programming**, the order of equations is irrelevant. Interchanging two equations does not affect the result. This is true of SABER [5] which employs a programming language called **MAST** [5]. MAST uses two different modelling techniques:

1. Modified nodal analysis:

By defining **n** nodes where the through variables at each node are determined so that to satisfy the across variables (or visa versa). For example for nodes **p** and **m**, by stating:

i(p->m) += v(p->m) / R , where R = constant

then the through variable i(p->m) will be determined so that to satisfy the condition for the across variable v(p->m). In the electrical domain, SABER [5], will solve the differential equations so that to satisfy Kirchoff's voltage (across variables) and current (through variables) laws. This can be extended to other domains.

2. Unitless variables:

Equations can be solved by means of unitless variables. A differentiator is shown below where SABER simply determines the first derivative of the unitless variable **in**.

e.g. out: out = d_by_dt(in)

More powerful combinations can be implemented by combining nodal (in terms of across and through variables) and unitless variables.

A SABER WIND FARM AND FACTS MODEL:

SABER was used to implement the wind farm / FACTS model. The overall system was split into various MAST templates (Fig.4) which made the overall model modular and easy to modify. The wind speed model provides a variable wind speed to the turbine model of Turbine 1. The turbine output is fed to the induction generator model. The generator outputs are 3 electrical nodes which represent the stator terminals. These are connected to the grid model. Note that all mechanical parts of the system were modelled as unitless variables while all electrical parts were modelled using nodal analysis. Nodal representation was required for the electrical parts in order to facilitate a straightforward connection of the FACTS to the turbines and the grid. The rest of the system (wind turbine models), were represented as a series of differential equations which were easier to model using unitless variables. Note that unitless variables were also used for the modelling of the FACTS controllers. Wind turbine 2 (Fig.4), is affected by wind farm aggregation effects. There are another three wind turbines modelled in the same fashion, not shown in Fig.4 for simplicity.

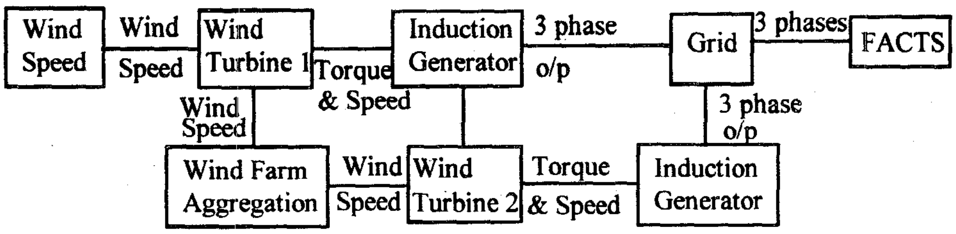

Figure 4: SABER Wind farm / FACTS block diagram

SIMULATION ACCURACY AND SIMULATION TIME:

The accuracy of the SABER simulator can be changed by means of two independent parameters, **ter** (truncation error) and **den** (density) [5].

1. Truncation error (ter):

In time domain analysis, as the solution of a system is approached, it becomes more accurate if the time increments are decreased. SABER uses a variable time step predictor-corrector algorithm which sets the time step according to the difference between an extrapolated and a calculated value of the system response. If this difference is smaller than the user defined **ter**, a larger time step is used, otherwise the time step is decreased.

2. Density factor:

SABER solves non-linear equations using a piece-wise linear evaluation. The variables of these equations are sampled before a piece-wise linear evaluation of these equations is determined. The density factor changes the number of samples for each variable so that the accuracy of the linearisation process can be changed by the user.

RESISTIVE BRAKE SIMULATION:

The resistive brake (Fig.5) is used here to dump the wind turbine electrical energy when the wind farm is suddenly disconnected from the grid.

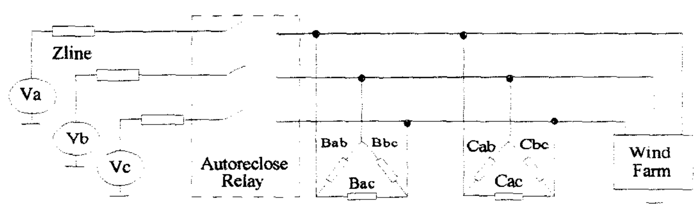

Figure 5: Resistive Brake - Wind Farm circuit

Without the brake (Fig.6), the self excited turbines had a high stator voltage as a result of the capacitance across them. This overvoltage makes grid reconnection unacceptable. When the brake was connected, it dumped the electrical output of the turbine and the voltage was almost stable (Fig.7), thus limiting the acceleration of the isolated turbines. This can be verified by looking at the induction generator rotor speed. Without the brake the turbine accelerates almost linearly (Fig.8), while when the brake was connected, the rotor speed stabilised due to the absence of accelerating torque (Fig.9).

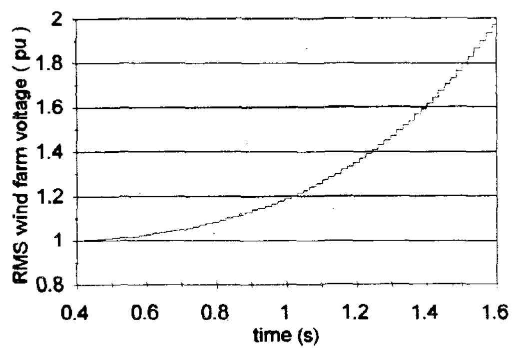

Figure 6: Wind farm voltage (without brake)

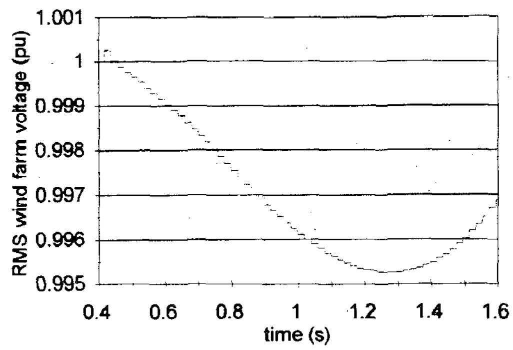

Figure 7: Wind farm Voltage (with brake)

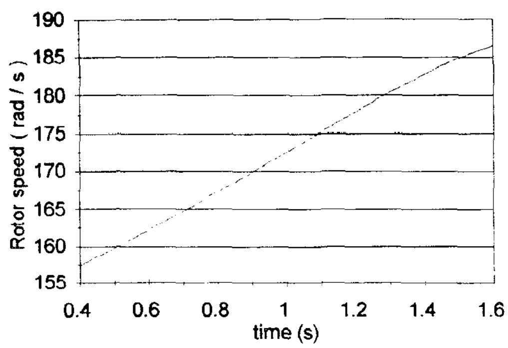

Figure 8: Wind turbine rotor speed (without brake)

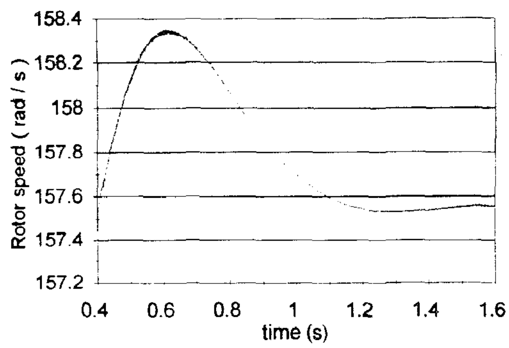

Figure 9: Wind turbine rotor speed (with brake)

UNIFIED POWER FLOW CONTROLLER (UPFC):

The UPFC comprises of two inverters, a series and a shunt. The shunt inverter is a 12 - pulse inverter bridge and provides the wind farm reactive power. The series inverter is a PWM inverter and it provides voltage control. Simulation of this system proved much slower than that of the resistive brake.

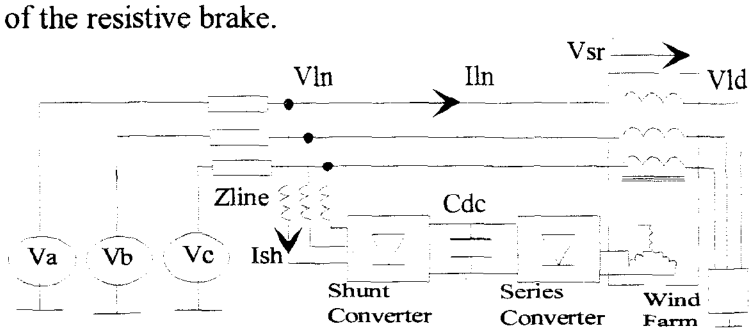

Figure 10: Wind farm - UPFC arrangement

The shunt branch was set so that to provide the whole of the wind farm reactive power. Fig.11 shows the reactive part of the wind farm current going to zero as a result of the UPFC. A SABER FFT analysis was performed (Fig.12), which indicated a considerable 11th and 13th wind farm current harmonic. The total harmonic distortion was 20%.

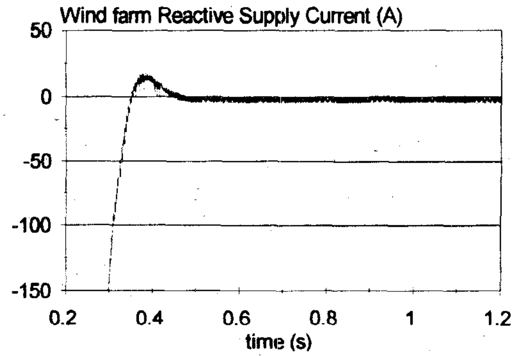

Figure 11: Wind farm reactive current with UPFC action

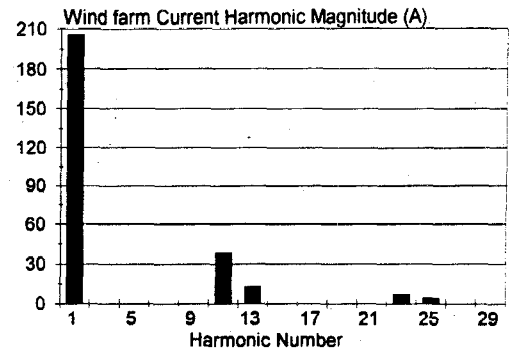

Figure 12: Wind farm current harmonics

The series branch was set to maintain the wind farm voltage at 1pu. Before the UPFC was applied (Fig.15), the load voltage was 10% below the nominal voltage, and varied about 6% between the extremes of 0.945 and 0.89pu. After the UPFC was applied (Fig.16), the voltage was fixed at 1.0pu and the overall variation in the voltage was about 2%. Note that the UPFC series branch was put into action at t = 0.3s.

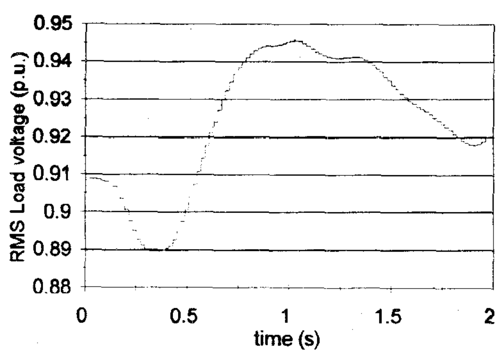

Figure 15: Wind farm voltage (before UPFC action)

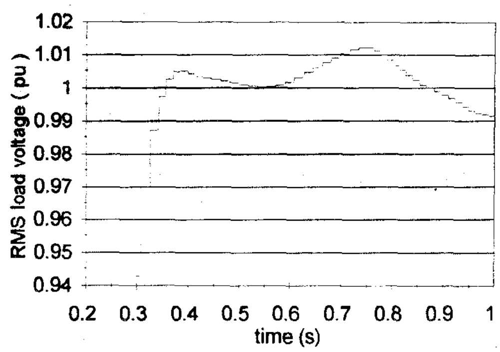

Figure 16: Wind farm voltage (after UPFC action)

CONCLUSIONS:

The interaction of wind farms and FACTS provides a difficult problem for the analysis of power systems that incorporate renewables. It was shown how SABER a special simulation package built around MAST was used to simulate a system containing a resistive brake and a UPFC. Finally SABER simulation results were used to indicate that the resistive brake can be used as a dump load for isolated wind farms and that the UPFC can provide both voltage control and the reactive power of a grid connected wind farm.

REFERENCES:

[1] A.Papantoniou, A.Coonick & L.Freris, "Islanding Problems of Grid-Connected Wind Turbines", Eighteenth BWEA Wind Energy Conference, Exeter, Sept.1996, pp.257-261

[2] A.Papantoniou, A.Coonick & L.Freris, "Modelling and Simulation of an ASVC Using SABER", Sixth International Conference of Power Electronics & Variable Speed Drives, PEVD96, 23-25 Sept.96, Nottingham, UK, pp.490,495.

[3] A.Papantoniou, A.Coonick & L.Freris, "Simulation of WECS", 1996 European Union Wind Energy Conference, 20-24 May 1996, Goteborg, Sweden, pp.432-435.

[4] L.Gyughi, "Unified Power - Flow Control concept for flexible AC Transmission Systems", IEE Proc., Vol.139, Iss.4, pp.323-331.

[5] Analogy, SABER user guide, Version 3.4, 1994.