CONDITIONING OF POWER GRIDS SERVING OFFSHORE WIND FARMS BASED ON ASYNCHRONOUS GENERATORS

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Abstract

Wind power is gaining momentum in the world´s energy balance. Several issues have to be addressed whenever power-generating devices are connected to the grid. This paper describes how wind farms affect grid voltages and how faults in the connected transmission system impact on induction generators in a wind farm. It will also be shown that, when the network is weak, local dynamic reactive power support may prevent voltage collapse and make it possible for the wind farms to recover and remain in service after a short-circuit event. A dynamic voltage control scheme based on a combination of SVC and STATCOM technology will be discussed.

1 Introduction

After decades in the starting block, wind power is finally taking off as a serious and accepted source of energy, sustainable and environmentally friendly. World-wide, more than 30 GW of wind power was in operation by the end of 2002, an annual growth of approximately 27%. It is expected that by the end of 2007, this figure will have increased to well over 80GW.

In Germany for example, ten years ago, wind power was of marginal importance. Today, with more than 12,000 MW in operation, the country is Europe's most important user of wind power. In the UK, more than 2000 MW of wind generation is expected to be installed by 2005. In Denmark, close to 3000 MW of wind power is now contributing more than 15% of the country's generation capacity.

2 Offshore wind generation: fast emerging

Increasingly offshore based wind farms, where large amounts of wind power generation (typically tens of MW up to several hundred) are located out to sea with the electrical energy brought to shore through large heavy duty underwater cables. The largest offshore projects now in operation are the 160 MW Horns Rev and the 160 MW Nysted, both in Danish waters. AC is utilized in both cases for landing the power. It is anticipated that AC transmission will be an economical and technically attractive option in many of the small to medium sized windfarm cases, and dynamic reactive power compensation will then form and integral part of the network scheme.

Evidence suggests that the increased revenue from exploiting higher wind speeds farther offshore can outweigh the increased cable costs and electrical losses. The most common wind power generator is based on the asynchronous machine, since it is robust and cost effective. Induction generators, however, do not contribute to regulation of grid voltage, and they are substantial absorbers of reactive power. Ideally, they need to be connected to very stiff grids in order not to influence power quality in a detrimental way. This is not the case in reality, however. Quite on the contrary, wind power is usually connected far out at the extremities of the grid, on sub transmission or even distribution levels, where the network was not originally designed to transfer power back into the grid.

The reactive power balance of asynchronous generators can be improved to a certain extent by use of the recently introduced doubly-fed rotor concept. To keep this technology within reasonable cost margins, however, rotor converter ratings must be kept limited to steady-state requirements only. During transient occurrences in the grid, the performance of doubly-fed induction generators (DFIG) may well prove inadequate to safeguard primarily voltage stability of the grid.

3 Sea cables: a key issue

Comprehensive sea cable networks add another dimension, calling for additional elaborate reactive power control. The overall scope of reactive power control should encompass the wind farm as well as the sea cables, to bring about a well regulated reactive power balance of the whole system, performing to the same demands on reactive power regulation as any other medium to large generator serving the grid.

Limits of transmission capacity of sea cables should be calculated with compensation, so half of the charging current flows to each end at maximum load. An example of transmission capacity for XLPE cables at four different voltage levels and as a function of cable length is shown in Figure 1 [1]. In the example, the cables all have a cross-section of 1,000 mm^2.

It can be seen that the power transmission capability exceeds 350 MW at a distance of 100 km and a voltage of 220 kV. At a distance of 250 km, the power transmission capacity is still 175 MW.

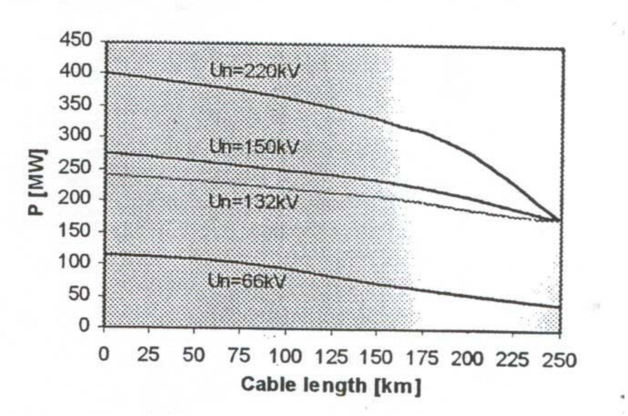

Figure 1: Limit of power flow as a function of length for compensated cables type 3x1x1,000 mm^2.

4 Requirements related to network connection

All national grid codes, even though several differences can be found, discuss the importance of grid support from all installed power generating devices. Many regulatory authorities require that the generators should be able to vary their reactive power output dependent on the grid voltage level. This requirement is a result of the desire to maintain voltage stability and limit dynamic voltage variations. Wind farms have often been excluded from these demands. They cannot, however, expect to enjoy this favoured treatment forever.

In the past wind power plants typically have had a small power rating, when compared to the strength of the connecting electrical network. The power system as such did not depend on the contribution from the renewable power sources. Under these circumstances the behaviour of the wind farms to faults in the network seemed to be non-critical and the manufacturers could design a simple control system that dropped out the wind farms whenever disturbed conditions occurred on the network.

Looking at the larger wind farms presently being planned this design philosophy becomes questionable. When a fault occurs in a power system the faulty part will normally be disconnected from the system. Thus if the fault occurred on the feeder to which the wind farm is connected it will be disconnected. But, if the wind farm is connected to the non-faulted part of the system it is desirable that the wind farm stays connected during the fault. As soon as the faulty feeder has been disconnected the wind generator should return to operation in order not to cause consequential loss of generation in addition to generating units connected through the faulty feeder. If a significant consequential loss of generation occurs it is possible that a system collapse could result.

Therefore the wind farm connection must be designed so that the wind turbines are capable of continuous uninterrupted operation during the protection clearance times for the faulted components (“ride-through capability”). Typically the time required in a transmission system is in the range 100-200ms. Increasingly windfarm connection agreements are specifically stating that “there is no reason to exempt wind generation from this requirement”.

5 Voltage control

Reactive power control is necessary to meet the criteria mentioned in Section 4 above. With synchronous generators, reactive power control is achieved by means of the exciter system. However, this is not possible for induction generators. An SVC positioned at the grid connection point acts as a central exciter system but with the advantage that reactive power can be controlled even when no power is generated.

The subtransmission, or even distribution, systems to which offshore wind farms may be connected are usually designed to distribute power from the main grid to remote customers. The system in most cases is very weak and a change in power flow direction will strongly affect the voltage level. Mechanically switched capacitor banks, (MSC), are often used to deal with voltage level problems. However, power production, and thus reactive power consumption, in wind farms vary with wind speed. The resulting frequent switching of MSC deteriorates power quality and decreases the lifetime of the MSC. An SVC, with continuously variable susceptance, is often a cost efficient alternative to several small MSC.

Several phenomena associated with power produced from wind, introduce voltage flicker on the connecting node, i.e. generators´ start and stop, wind speed variations, and tower shadow effects. This flicker has a detrimental effect upon other components connected to the grid, causing complaints from power consumers. By connecting an SVC at the grid connection points, this flicker can be mitigated.

6 Induction generator behaviour at short-circuit

The behaviour of the induction generator during network faults and fault clearance is governed by simple physical principles that apply to this kind of machines. A broad overview is given in order to explain the problems related to network connection of large wind farms utilising such generators.

6.1 Induction generator basic structure

The reason for the attractiveness of the induction generator is its extremely simple basic design, making it small, robust and cost-effective. The rotor simply comprises a stack of iron plates with axial conductive bars, which are connected between short-circuiting endrings. The rotor is mounted in the stator, coaxial and with a small airgap as shown in Figure 2.

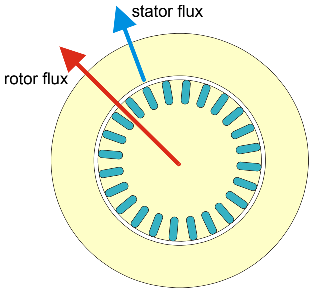

Figure 2: Structure of the induction generator.

The small airgap causes a strong magnetic coupling between any winding on the stator and the rotor structure. The main portion of the magnetic flux passing through the stator winding also must pass through the rotor. But the rotor cage is a highly conductive structure, which at any time opposes every change of the magnetic flux in the rotor. It serves like a magnetic screen that prevents external fields from penetrating into the rotor. Forced, fast changes of the magnetic flux in the rotor can only be achieved at the expense of large stator (and rotor) currents. Due to their close linkage the rotor flux follows the stator flux with a first order delay of about 100 ms.

6.2 General principles of operation

When the machine is connected to a strong network, the applied voltage determines the magnetic stator flux, because the derivative of the stator flux must equal the applied voltage. The network voltage creates a magnetic stator flux, which rotates with constant speed in the airgap. The rotor flux derivative, and consequently the stator current, can be low only if the rotor rotates almost synchronously with the stator flux. This is highlighted in the top graph in Figure 3, which depicts the stator current versus the rotor's speed deviation from synchronous speed at constant stator voltage. It is characteristic that the induction machine draws a lot of current at start and at high overspeed.

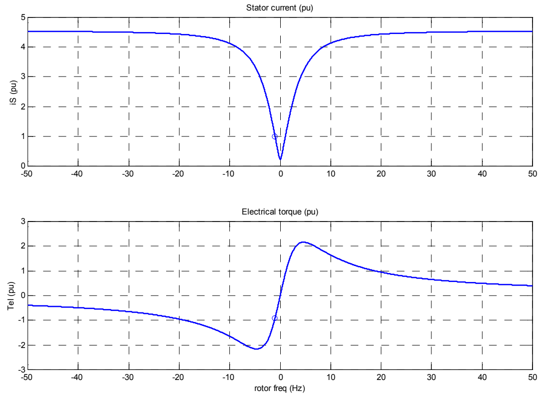

Figure 3: Typical induction generator characteristics versus rotor frequency $(f_{network} - f_{mech})$ at fixed stator flux: stator current (upper) and electrical torque (lower).

Small deviations from synchronous speed, on the other hand, excite rotor currents that produce mechanical torque. This is shown in the lower graph of Figure 3. It can be seen that the torques having the highest magnitudes, the 'pullout' torques, are produced at quite small speed deviations from synchronous speed. The normal operation range for the induction generator is on the slope between the positive and negative pullout torque. The nominal operating point is marked by a small ring in Figure 3.

6.3 Electrical effects at short-circuit

Now, if a short-circuit is applied to the network close to the generators, the stator voltage becomes zero. The stator flux, being the integral of the applied voltage, then stops because its derivative becomes zero. The rotor flux however is captured by the rotor cage and cannot decrease instantaneously. Therefore, initially the induction generator, just like a synchronous machine, delivers reactive power to the fault. The machine thus contributes to the current through the fault.

But the current in the generator demagnetises the rotor and both the rotor flux and the stator current disappear in about 100 ms. The stopped and still-standing stator flux, which is captured by the short-circuited stator winding, creates a braking torque on the rotor. The flux decays in about the same time as the rotor flux, i.e. in about 100 ms. Figure 4 shows the rotor flux and the stator currents at a short-circuit very close to the generator.

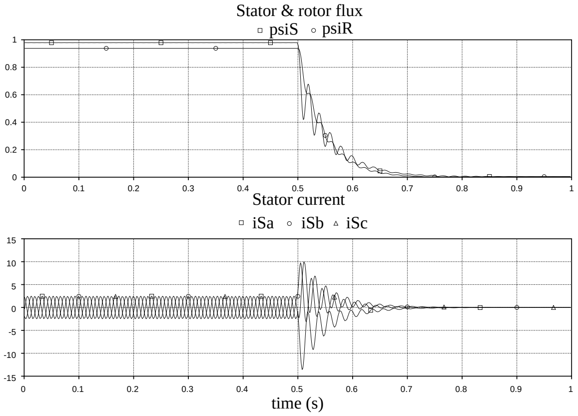

Figure 4: Short-circuit of the induction generator close to its stator terminals, stator and rotor fluxes (upper), stator phase currents (lower).

6.4 Mechanical effects at short-circuit

A short-circuit on the transmission system, somewhere between the generator and the receiving network, prevents any electrical power from passing through that point as the voltage becomes zero. The loss of the electrical output from the generator causes a mismatch between decelerating electrodynamic torque and the (initially unchanged) accelerating mechanical torque on the generator shaft from the wind turbine. Thus the generator will accelerate during the short-circuit. Due to the involved mechanical time-constants in the wind turbine blade control system it is not possible to reduce the turbine torque during the short-circuit.

The total inertia constant for the generator and the turbine is a few seconds. Typically most of the inertia is located in the wind turbine and only approximately 20% of the inertia relate to the generator rotor. These two masses are connected through a soft torsional shaft exhibiting a resonance frequency in the range of 1-2Hz. Figure 5 shows the speed of the induction generator and of the wind turbine, when the wind farm is operating at its rated power and a short-circuit occurs close to the generator terminals. The curves show that the average speed increases with approximately 6-7 Hz per second as long as the short-circuit is applied. Thus the negative slip frequency increases during the short-circuit. It has already been pointed out in Figure 3 that the induction generator current increases rapidly, when the rotor frequency deviates from the synchronous speed.

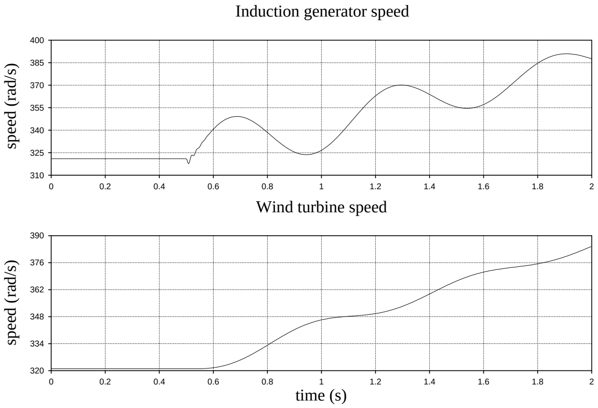

Figure 5: Speed of generator and wind turbine at short-circuit.

7 Recovery from a fault

The line, where the short-circuit arose, will automatically be disconnected from the rest of the transmission system with little delay, typically within 100-200 ms. If the isolated, faulty part does not involve the wind farm, it is anticipated that the latter restores its steady state generating operation, when the network voltage returns after fault clearance. However, as it has been shown above, the machine has been demagnetised during the short-circuit and its rotor speed has increased so that the negative slip has increased. Both these factors impact on the process of recovery.

7.1 Effects of demagnetisation

Consider first the fictitious case that the rotor speed of the generator is constant during the short-circuit. When the network voltage returns a stator flux is being impressed on the generator stator. But the rotor cage prevents the stator flux from rapidly entering into the rotor due to the screening effect caused by the rotor cage. During the rotor magnetisation (time constant 50-100 ms) the stator will carry a large reactive current. Depending on the network strength this magnetising current causes a voltage drop, which lowers the generator terminal voltage below, possibly even significantly below, its rated value. If the rotor remains rotating with synchronous speed the stator flux will penetrate into the rotor and the machine will finally be magnetised. When the network is weak it appears approximately like a current source as indicated in Figure 6. The equivalent impedance in the rotor circuit is high, when the slip is low. Accordingly most of the injected current passes into the magnetising inductance of the generator.

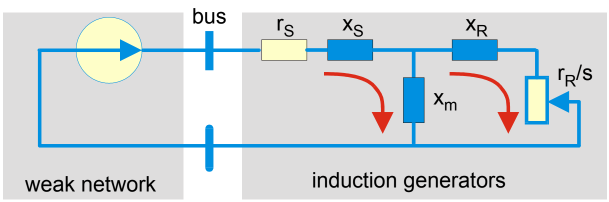

Figure 6: Magnetising the induction generator with normal rotor speed.

7.2 Effects of overspeed

If the short-circuit duration is long and/or the magnetisation of the induction machine takes too long, the generator speed increase becomes considerable. This means that the absolute value of the slip increases and the impedance of the rotor circuit branch lowers. When the feeding network is weak almost all the injected current passes through the rotor circuit and almost no magnetising current results as shown in Figure 7.

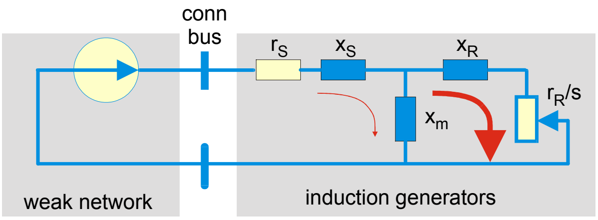

Figure 7: Magnetising the induction generator at overspeed.

7.3 Conclusion

The induction generator can recover successfully from the short-circuit fault only if it becomes magnetised sufficiently fast so that it can produce torque and reduce the generator rotor overspeed. If the overspeed becomes too large the generator will pass over the pullout frequency and then it will consume large amounts of reactive power. If the network is weak this situation will cause a voltage collapse to occur in the transmission system.

8 Improvements by utilizing SVC

A Static Var Compensator, SVC, can be provided as a reactive power source located close to the machine. This approach brings about some advantages:

- one device serves the whole wind farm
- the voltage in the connecting point is stabilised by a voltage controller
- Flicker due to tower shadow effect and variations in wind speed will be decreased

A typical system has been chosen and studied (Figure 8). The layout of this generic system is based on related cases and studies.

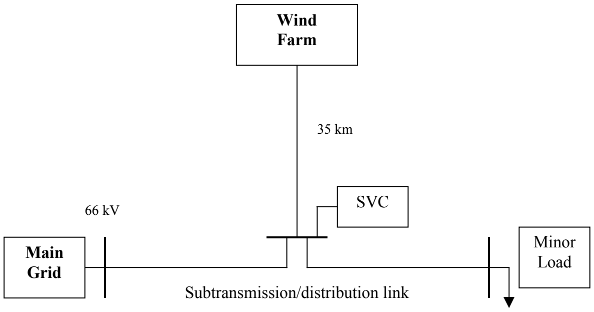

Figure 8: Set-up of generic study of grid connection of off-shore wind farms.

8.1 Voltage stability

Starting and stopping of the generators is critical in many applications. Induction machines draw considerable reactive currents when the stator gets energised, even if the turbine is accelerated to synchronous speed before being connected to the grid. This results in a period of decreased voltage. In this paper, the phenomenon is simulated with a small example.

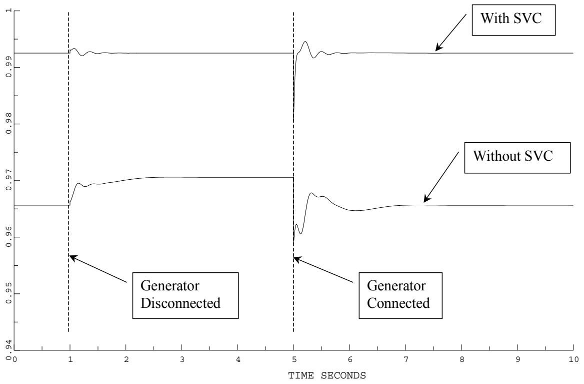

Figure 9: Voltage variations at the minor load associated with start and stop of one 1.5MW wind turbine.

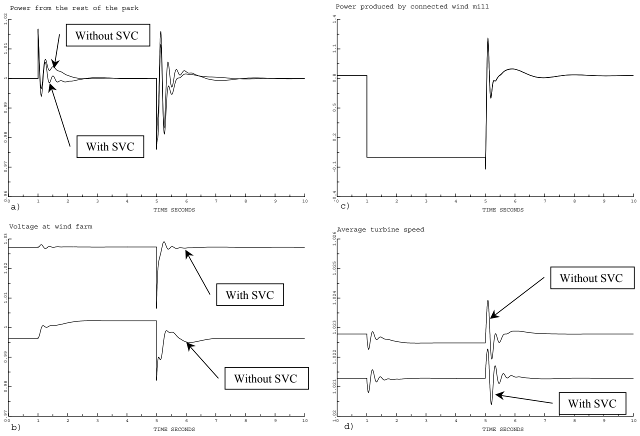

Figure 10: The same event as in Figure 9 but other data presented. a) Power production from the rest of the wind farm – also affected by the voltage variation, b) Voltage at the wind farm, c) Power produced by the switched generator and d) Average turbine speed.

The total wind farm generation is 60MW in this example and the switched generator produces 1.5MW. A shunt capacitor producing 500kVAr is connected at the same time as the generator. The turbine is increased up to synchronous speed before being connected. Figure 9 and Figure 10 show that the SVC has a stabilising effect on the voltage variation.

8.2 Using SVC to improve recovery from network faults

It was shown in Section7 that it is crucial that the induction generator is magnetised very rapidly, when the network voltage returns following a network fault. If this cannot be achieved sufficiently fast the generator will speed up and then the slip cannot be brought down close to zero by the electrical network. The speed reduction must then be achieved using the mechanical turbine blade angle control system. The time constants then become much larger than the typical short-circuit duration and the wind turbine generator will require a restart in order to regain its prefault power generation operation. When the electrical network is weak the behaviour of wind farms at network faults will be strongly improved by reactive power support at the connection point.

Figure 8 shows the set-up of a generic simulation of the recovery from a network fault. It is assumed that the network has a short-circuit strength of ten times the total rated power of the wind farm generators. Additional transformers are inserted between the subtransmission system and an intermediate voltage level (20-36 kV) and further from this intermediate voltage level down to the low-voltage internally used in the wind farm towers. It is assumed that the no-load reactive power consumption is compensated internally in the windmills.

Figure 11 shows the simulation results when a 200 ms fault is applied at the high-voltage bus at the grid connection point and when the SVC is not in operation. It is assumed that the turbine power is constant.

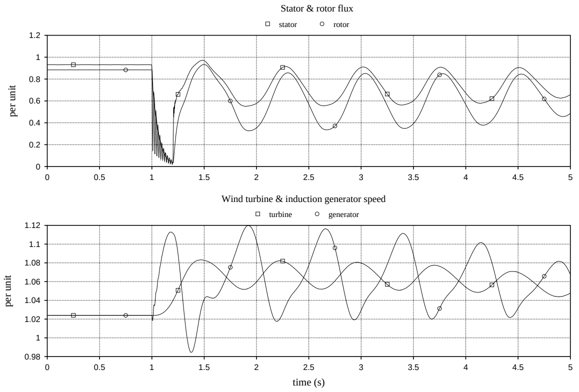

Figure 11: Simulation results without SVC.

The upper diagram shows the stator and rotor flux in the generators and the lower diagram shows the speeds of the wind farm turbines and the induction generators. The simulation indicates that the wind farm will possibly recover from this fault, but the network is very close to a voltage collapse situation.

Figure 12 shows the simulation result for the same event as in Figure 11 when an SVC connected to the intermediate voltage level and having the same rating in MVAr as the generators have in MVA is used.

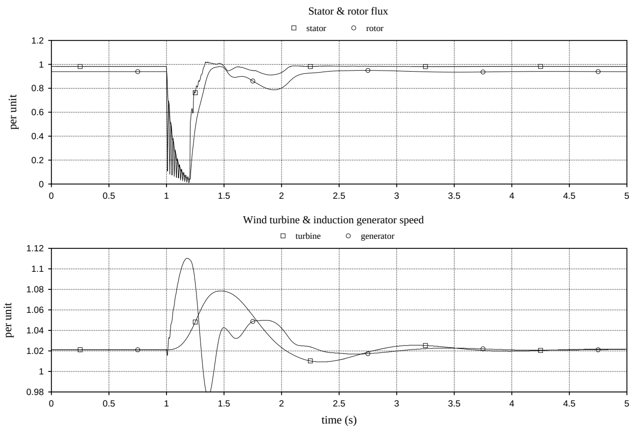

Figure 12: Simulation results with SVC.

The stability clearly has been improved significantly and the generators recover to the prefault generation within a second. The critical point occurs a few hundred ms after the fault clearance and at that time it is clear whether the recovery will be successful or not.

Although this simulation is very much simplified it gives a general indication that the conditions at fault recovery should be looked at if the (post-fault) network strength is lower than ten times the rating of the generators.

9 SVC implementation

The SVC today can be obtained in two different versions. The first SVC approach is based on conventional capacitor banks together with parallel thyristor controlled inductive branches, which consume the excess of reactive power generated by the capacitor bank. This type of equipment can be directly connected to the intermediate voltage bus, which interconnects the wind farms (up to 36 kV). It is also possible, but less cost effective, to connect the SVC at the high-voltage network by a dedicated transformer.

The second alternative implementation of the SVC makes use of a power electronic voltage source (VSC). The converter utilises semiconductors having turn-off capability. The converter can inject or consume reactive power to/from the bus where it is connected. This application of VSC technology is usually referred to as STATCOM (Static Compensator). This alternative has the benefits of a smaller footprint as large air-cored inductors are not used. Another advantage stems from the fact that a smaller parallel capacitor bank can be used, as the converter itself may contribute reactive power.

By combining the two types of schemes, a cost-effective dynamic compensator can be achieved, rated for a high dynamic yield during a short time and a lower yield for steady-state operation, Figure 13.

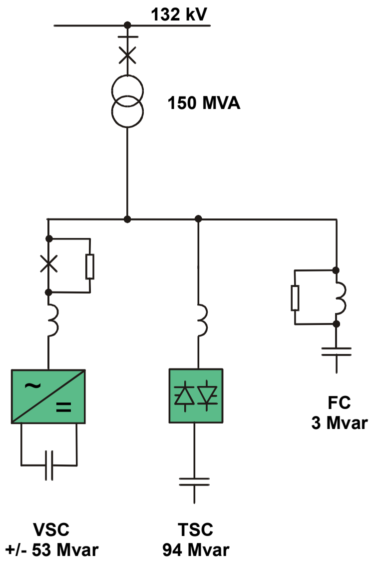

Figure 13: Combined VSC and TSC scheme.

Thus, Figure 13, shows a typical example, a VSC rated at –/+53 MVAr is combined with a Thyristor-Switched Capacitor (TSC) rated at 94 MVAr and a 3 MVAr Harmonic Filter, giving a total output of –50/+150 MVAr. The purpose of the scheme is to yield dynamic VAr compensation of a large sea-based wind farm. The TSC will only operate in cases of potential voltage collapse until the wind farm can be tripped or until the fault has been cleared, i.e. only for a short duration, and can therefore be rated in a very economical way.

10 Conclusion

In this paper the voltage variations associated with an offshore wind farm being connected into an existing power network have been discussed. The paper concludes that an SVC at the grid connection point can mitigate voltage problems.

In addition to this, the instability that can occur in a wind farm due to network faults and the recovery from such faults have been discussed. The risk of voltage collapse emerges from the nature of the induction generator, which consumes large amounts of reactive power when its speed slightly deviates from the synchronous speed. There is a time window when it is possible to catch the accelerating turbine after fault clearance, but it requires fast magnetisation of the generator. This process can be dynamically supported by an SVC, a STATCOM, or a combination of both, installed close to the connection point of the wind farm.

It is clear that the resilience of windfarms to remain connected during network faults will become increasingly important as the ratings of planned wind farm installations become significant when compared to the network strength at the connection point. In addition as the percentage of wind farm generation becomes a significant part of the UK generation portfolio, greater reliance on the stable operation of wind farms will be essential to maintain total grid security during major system incidents.

11 References

[1] F. Rudolfsen et al: “Power transmission over long three core submarine AC cables”, *3rd international workshop on transmission networks for offshore wind farms, Royal Institute of Technology,* Stockholm, 2002.

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