21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

C1-107

CIGRE 2012

# Parallelling offshore wind farm HVDC ties on offshore side

**V. F. Lescale***
**Sweden**

**P. Holmberg**
**ABB HVDC**
**Sweden**

**R. Ottersten**
**ABB HVDC**
**Sweden**

**Y. J Häfner**
**ABB HVDC**
**Sweden**

## SUMMARY

In some regions where wind farms are connected to the main grid through HVDC links, the parallelling of these links on the offshore ac side has been advocated or even required. Such parallelling implies the creation of an ac island which is far from resembling a typical ac system. Mainly because of:
A) Wind turbine driven generators are not normally of synchronous type.
B) The "loads" offshore will consist of HVDC links transporting the power to the mainland, and these links are entirely different from normal loads; mainly because the control system will regulate them.
C) The offshore network will mainly consist of rather short cables. Compared with transmission lines, they have much higher shunt susceptance (capacitance) and lower losses.

**Why parallelling?**

- Intuitively, the loss of one HVDC tie should result in a smaller loss of power onshore than would be the case with independent HVDC ties, but this is only true when the number of ties grows.
- A good dispatch between the ties can be used for minimizing the losses, including those in the on-shore ac system

**Why not to parallel?**

Fully utilizing the transmission capacity of the HVDC links is elusive: If the loss of an HVDC link results in serious overload to the remaining links it may cause a cascading loss of all of them. The whole sequence may be extremely fast; faster than can be handled with breakers. Power curtailments may become necessary in the dispatch, and their present value may be extremely high

**To consider if the decision is to parallel**

- Generator types will affect their transient behavior and the dynamic overload levels imposed on the HVDC links.
- HVDC converter characteristics for active and reactive transient and temporary behavior. Strategies and principles for control have to cope with normal and emergency conditions.
- The regulation and market environment: Dispatch constraints needed for parallelling may result in undue present value of costs.
- The extreme costs of space and weight for platform-installed equipment. Some solution that might appear attractive onshore might not be so offshore.

## KEYWORDS

HVDC, Wind power, Offshore wind power, HVDC VSC, Frequency control, Parallelling.

(*) viles.1110@tlia.com.

# 1 Introduction

In some regions where wind farms are connected to the main grid through HVDC links, the parallelling of these links on the offshore ac side has been advocated or even required. Such parallelling implies the creation of an ac island, which at first glance could be thought of as falling on the normal category of ac systems, with synchronous generators, a transmission system, and loads. In reality, there are some very important differences that must be addressed, as discussed in this article.

# 2 Why paralleling?

Parallelling can bring about some advantages. The most important one may be that the loss of an HVDC tie should result in a smaller loss of power onshore than would be the case with independent HVDC ties. This may be true when the number of ties grows.

Another advantage of parallelling is that a good dispatch between the ties can be used for minimizing the losses, including those in the on-shore ac system.

# 3 Why not to parallel?

Parallelling has also some disadvantages. If the loss of an HVDC link results in serious overload to the remaining links it may cause a cascading loss of all of them. Depending on the overload, the phenomenon may be extremely fast; faster than could be handled with breakers.

Avoiding this risk will lead to a generation dispatch that will not make full use of the installed capacity. In regions where the legislation mandates that the generation owner be paid for the available energy, rather than the delivered energy, the reduced dispatch can become quite expensive when integrated along the whole useful life of the ties (typically 30~40 years)

# 4 Important aspects to consider if the decision is in favor

If the balance between advantages and disadvantages results in a decision to parallel, several functional and economical aspects will have to be considered and dealt with. The aspects to considerare caused by the very important differences between a normal ac system and an offshore wind farm or cluster of farms. The main differences are discussed below:

## 4.1 Synchronous generator based system vs DFIG based system

In a normal ac system the vast majority of generators are of synchronous type. These generators have an electrical frequency that is tied to the mechanical speed. This means that when there are unbalances between the electrical and mechanical power in a rotor, the mechanical speed will change, and thereby its electrical frequency as well. This is very useful, since the rotational inertia evens out such unbalances by sharing the energy among the generators until the central, economical, dispatch optimizes the individual powers.

Contrasting this, in an offshore wind farm, most if not all of the generators are of DFIG (Doubly-Fed Induction Generator) type or, possibly, of full-size back-to-back converter connected type, and will probably continue to be so in the near future. In generators of these types the tie between the electrical frequency and the mechanical speed is not fixed. For example, see Figure 1, in a DFIG; the “tie” is mainly determined by the frequency fed to the rotor windings. This frequency comes from a converter in which the control usually aims at optimizing the generated power for the available wind [1], [3].

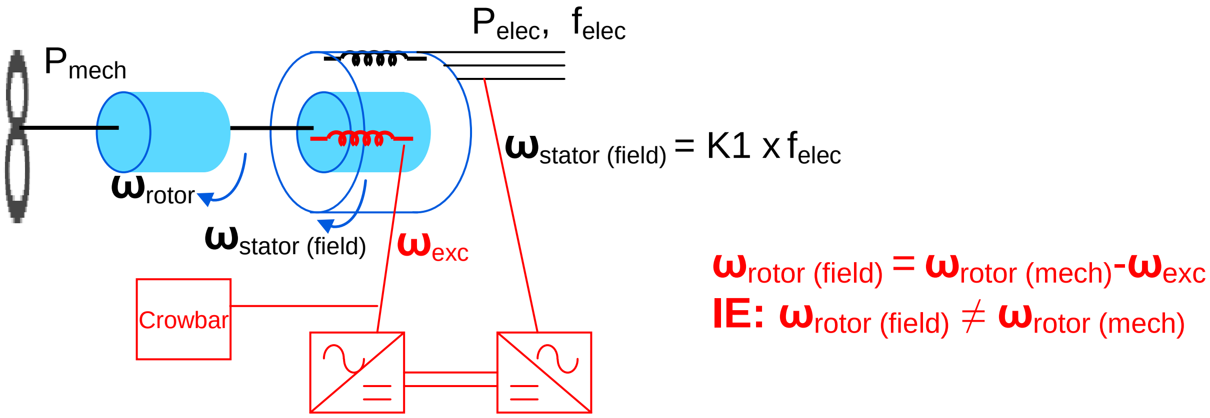


**Figure 1.** DFIG (Doubly-Fed Induction Generator).

The decoupling of the mechanical speed from the ac system side means that if/when there are unbalances elsewhere in the system, and the frequency changes, the rotor will not absorb a share of the unbalance: it will plough along, following its ordered function: maximum power for the available wind.

The frequency in an islanded offshore wind farm will thus have to be controlled by the HVDC converter evacuating the power.

## 4.2 Normal loads vs HVDC VSC converters

In an ac system, the “normal” loads do not try to keep the frequency of the system, although many loads exhibit a frequency dependence that lowers the power for decreased frequency.The frequency control is left to the synchronous generators.

By contrast, the main “load” in the wind farm will be the HVDC converter evacuating the power. This converter will have to provide a voltage reference for the DFIG’s to act against, and this reference will be provided with a controlled frequency. Furthermore, as the offshore farm generators will have limited possibilities to control the voltage magnitude and reactive power, this function will also fall on the HVDC converter. The combination of these two requirements has so far resulted in deciding for VSC-type HVDC converters (Voltage Sourced Converter).

HVDC converters of VSC type have several advantages, but they do not behave as a normal “load” would: When the generated power increases, the converter will keep the frequency and will absorb more power. This is good as long as the generated power stays within the capabilities of the converter. If the capability is exceeded, the main limitation of VSC converters appears: low thermal inertia: The VSC capability to handle overloads is extremely time-limited. Even for moderate overloads, the available time to control them might preclude the use of breakers.

## 4.3 The interconnection system

In an offshore wind farm the interconnections will consist of relatively short subsea ac cables. This will result in high shunt susceptance, due to the cable capacitances, and low losses, due to the lengths.Compared to a normal ac system, these aspects lead to the following differences: The higher shunt susceptance will result in a need to keep the voltage magnitudes within tight margins. The lower losses will mean that power swings will have poorer inherent damping.

# 5 Operation principles for parallel operation

If the decision is to operate two or more offshore wind farms in parallel some operational principles will have to be observed. These principleshave been investigatigated in the authors' group for assessing the technical feasibility of parallelling HVDC links using VSC converters.

The investigations have looked into steady state operation with different control principles, and looked into the transitions between parallel operation and isolated operation: from isolated into parallel in a planned manner, and from parallel into isolated in both, planned and sudden manners. The results have shown that this is possible but the controls have to observe certain rules. It has also been found that it is very important to properly consider the additional requirements on the higher level controls and communication, and the limitations on the system performance.

Figure 2 shows the process of synchronizing two wind parks in parallel on the offshore ac side, where each wind park is connected to the main onshore grid by an HVDC Link. The request to initiate synchronization is given at time 0.0s.

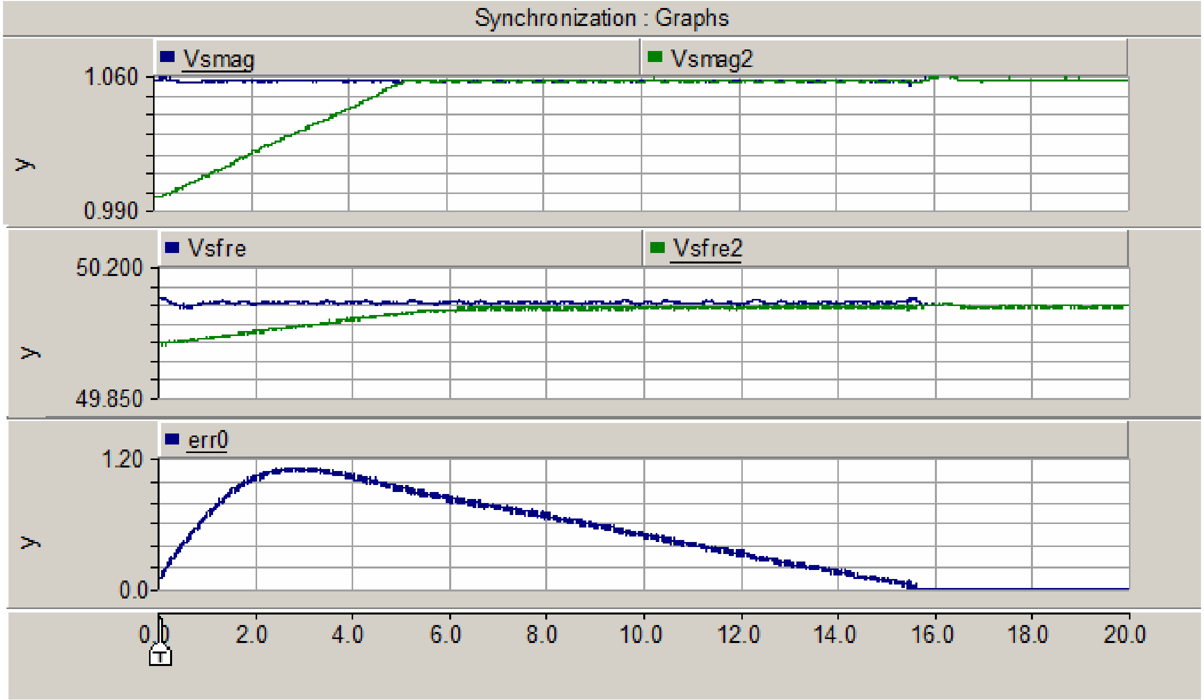
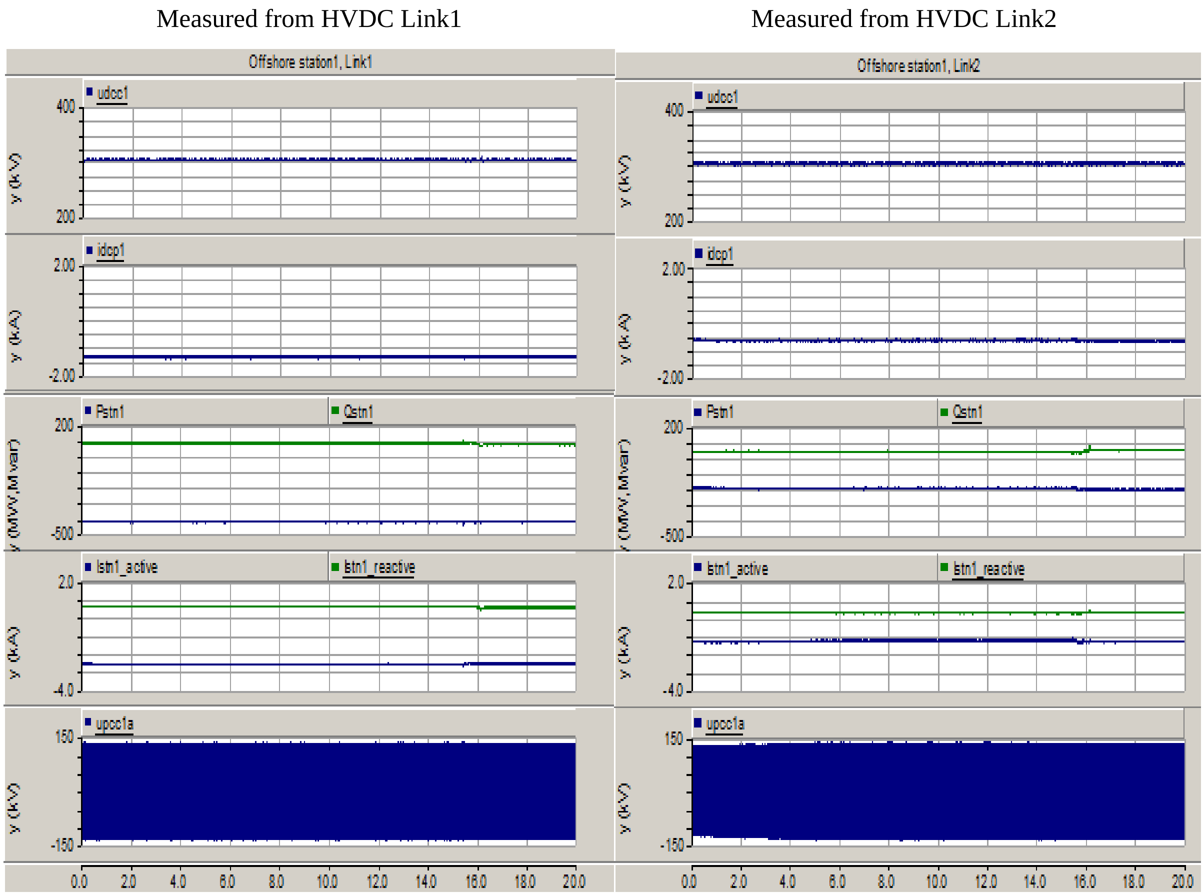


**Figure 2 Part a:** Simulation of connection of two island wind farm and parallel operation of HVDC links. Vsmag/Vsmag2: voltage magnitude of wind parks 1 and 2; Vsfre/Vsfre2 : frequency of wind parks 1 and 2; err0: phase difference (in radians) between wind parks 1 and 2.

As can be seen in Figure 2 Part a, there is a voltage magnitude difference (refer to plot 1), frequency difference (refer to plot 2) and phase difference (refer to plot 3) before the synchronizing ac breaker is closed. The HVDC converter which is responsible for synchronization starts to adjust its voltage magnitude, frequency and phase. At the time around 15.7 s, the two wind parks reach almost the same voltage magnitude, frequency and phase angle and the breaker is closed. Parallel operation of the two links starts from this time. The two transmission links shows stable operation before, during and after the connecting of the two wind parks, which is demonstrated in Figure 2 Part-b.


Measured from HVDC Link1

Measured from HVDC Link2

**Figure 2 Part b:** Simulation of connection of two island wind farm and parallel operation of HVDC links. Udcc1: DC link voltage; idcp: current in DC cable; Pstn1/Qstn1: active and reactive powers; Istn1_active/Istn1_reactive: active and reactive currents; upcc1a: instantaneous voltage of phase a.

## 5.1 Voltage and reactive power control principles

Operation in parallel in a system with low series impedances (short ac ties) and high shunt susceptances (ac cables) means that, voltage-wise, all ac busses will be tightly coupled to one another as will be the reactive power to the voltage levels. Similarly to frequency control, not more than one converter can be in stiff voltage control, and the most appropriate is that all of them operate with droop. The extension here is that a system with droop will benefit from a reactive power dispatch that can operate on the set points, and optimize the reactive power flows . In contrast to the active power dispatch, the onshore reactive power dispatch does not have to be coupled to the offshore one.

## 5.2 Frequency and active power control principles

As mentioned above, a typical isolated HVDC link operates in stiff frequency control; i.e., without droop, and the generators, DFIG's, are operated at the power they can generate. The frequency control (droop) of the generators comes into action only if the overfrequency exceeds a certain threshold of 0.1~0.2 Hz [2]; i.e., they operate in the vertical line of the characteristics shown in Figure 3.

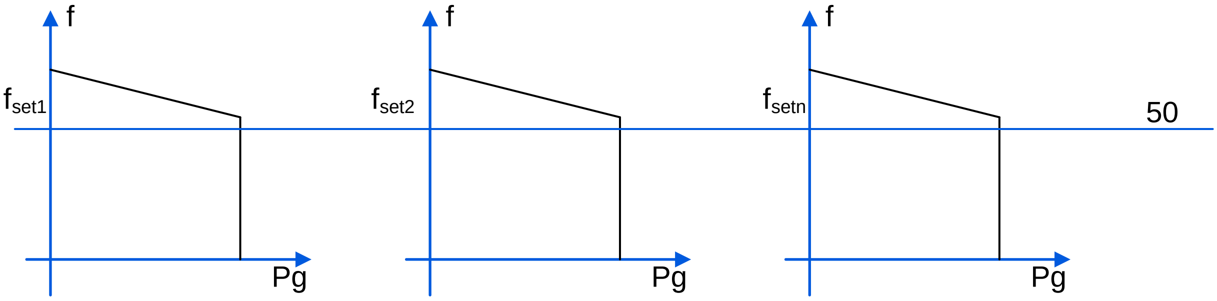


**Figure 3** Parallel operation of wind generators. No frequency control in normal operation. The frequency control is left to the converter. Droop is only active for overfrequency.

For operation in parallel, there are three possible, practical, strategies for frequency and active power control:

A) All offshore HVDC converters are in frequency control, with the same pu droop in all of them. Good load sharing can be achieved by sacrificing the stiff frequency otherwise considered normal in isolated farms. However, unexpected large load unbalances can occur under special conditions,. For instance, if the onshore AC grid experiences a frequency increase, and it requests the wind power imported by HVDC link to respond with “frequency dependent power reduction”, the offshore converter(s) will have to raise their frequency to signal the turbines to reduce the generation.

B) All offshore HVDC converters are in frequency control; however, one of them is in stiff frequency control, while the others use droop. As long as the wind differences between farms are not too large, a fixed frequency will be kept, and load sharing can be achieved by smart power dispatch. It should be noted that this strategy imposes high requirements on the communication between the central control and the individual converter controls: mainly to avoid overloading the converter in stiff frequency control, but also to avoid spurious load flows.

C) One offshore HVDC converter is in stiff frequency control, all the other converters are in stiff power control. Again, as long as the wind differences between farms are not too large, a fixed frequency will be kept, and a smart dispatch keeps a proper load sharing. This strategy also imposes high requirements on communication and control.

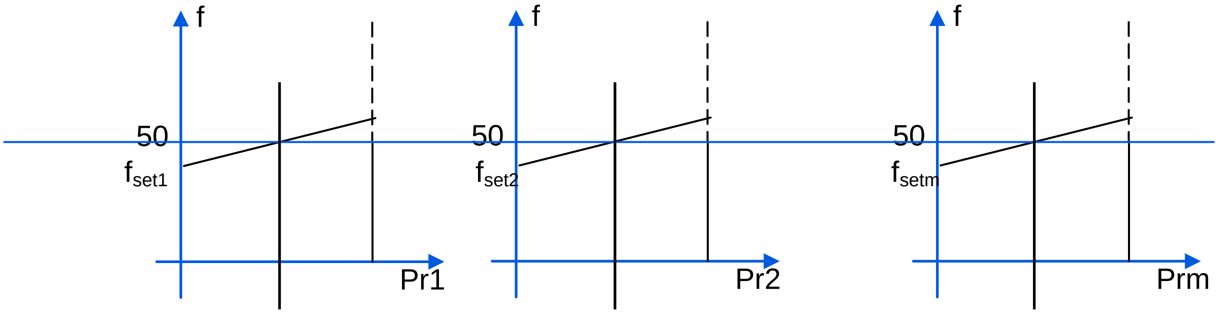


**Figure 4.** Parallel operation of HVDC converters. Frequency control and power sharing are achieved by characteristics with droop. Each characteristic can be shifted by the central dispatch to change the power share.

Strategy A) is illustrated in Figure 4. Changes in wind and/or disconnection of a generation group or of an HVDC link will change the total power, but the power balance between links will be kept. The temporary response will be good with droop, but power variations will result in a frequency deviation.

Restoring the frequency to the desired one has to be done through dispatch, just as is done in normal ac systems, by readjusting the set points of the droop characteristics. This can be done without special requirements on the speed of communication and control. A properly done dispatch will help in reducing the total losses, including those in the onshore ac system, especially if the HVDC links have different onshore terminal locations. A proper dispatch should also, of course, respect the limits found in studies.

It should be pointed out that in strategy A) significant transient unbalances in load may occur between HVDC links from different supplier due to different details in the design and implementation of the dynamic controls. Proper coordination has to be achieved by studies to define the transient functions and settings.

Of all three strategies, C is the one that has shown to be most robust in its behavior, but both B) and C) impose heavy requirements on the communications and control, especially for sailing through loss of the converter in stiff frequency control, as this forces the function reassignment to a preselected converter, and this has to be done very quickly and securely.

In general, a good communication system is a pre-condition for parallel operation, regardless of the selected control strategy.

# 6 Loss of one HVDC link

Apart from the loss of generation, which can be handled rather easily, the other contingency to deal with is loss of a converter, even though converter trips are rare. In case of loss of a converter, the complete power will be shared by the remaining ones. If this results in extreme overload, the converters will trip in cascade. To ensure that the new state of operation (emergency) will be survivable, the total power dispatched in normal state for the offshore island will have to take into account the possible contingency, just as in an ac system the generation dispatch considers the transmission limitations for e.g., loss of a line.

## 6.1 In the first milliseconds

Figure 5 illustrates what happens upon loss of one of the links: Link n$^o$ 1. The new conditions are shown by the red lines.

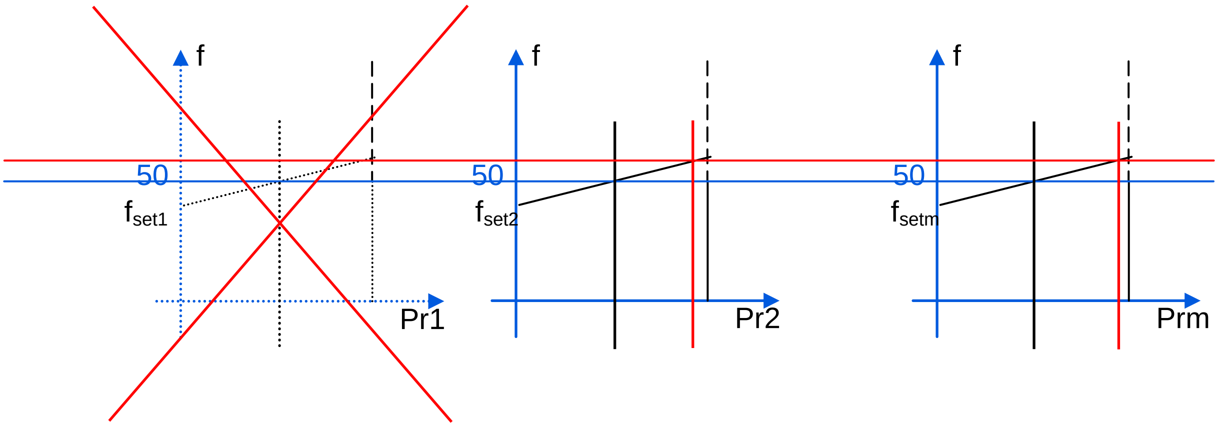


**Figure 5.** One converter has been lost, for whatever reason. The converters will move the frequency up, as defined by their droop and dynamic characteristics.

In the milliseconds following the loss, the power output of the generators (DFIG's and fully converter connected generators) will be constant, even if the frequency moves quickly up by virtue of the droop control in the converters. The total power will now be shared by the remaining converters. Some generators might be tripped to reduce the total power.

## 6.2 In the seconds following the contingency

If the steady state power dispatch before the contingency was not excessive, the system will survive and enter new operating conditions. The main change in these seconds is the reaction of the turbine governors, as the frequency enters the droop region they will reduce their power because of the overfrequency. The system will then have stabilized, but at an emergency state in which the frequency is not normal, and a new contingency would perhaps not be survived. This is illustrated by the red line in Figure 6.

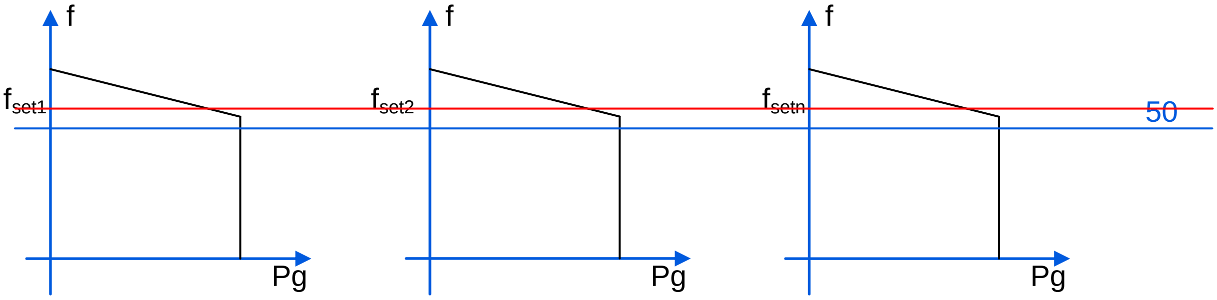


**Figure 6.** The increase in frequency moves the generators into the droop region, and they reduce their power. The frequency is still high.

## 6.3 Restoring normal state after the emergency

After surviving the emergency state, the central dispatch may shed some more generators or open some offshore ac ties, but more importantly: it will give new reference points to the frequency control of the converters.

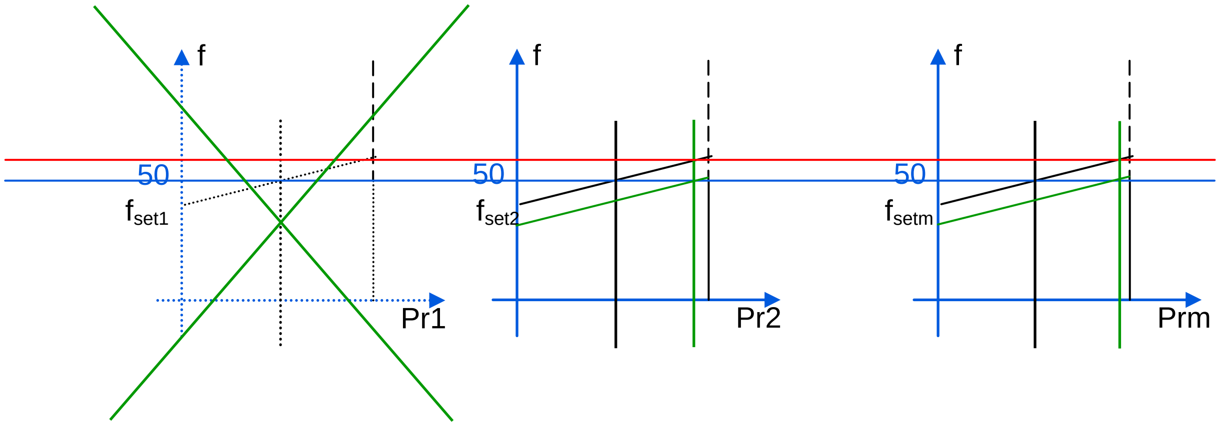


Figure 7. After surviving the emergency state, the central dispatch will give new reference points to the frequency control of the converters (green lines), and may even shed some more generators.

The two actions ensure that the system enters a new normal state. In it, the frequency is restored and the system is again robust enough to be able to survive a new contingency. It should also be noted that the new dispatch is optimized for the new conditions, resulting in minimum losses in the onshore system. This is illustrated by the green lines in Figure 7.

## 6.4 Strategies

In a system with each wind farm connected to a single link of the corresponding power the dispatch is free, as the only risk incurred is the loss of that link and its power. In a system with links connected in parallel, the generation dispatch cannot be at the total power of the links, as this would risk losing all the farms. The main message is that unless more transmission is installed so as to provide redundancy the generation will have to be curtailed but studies can minimize the curtailments.

A partial solution is to connect in parallel only as long as the total generated power can still fit into N-1 conditions, where “1” is the largest link. Beyond that point, segregating one or several farms with corresponding links into islands can be a solution. Each new island will have to either be capable of surviving its new N-1 conditions, or be small enough so that its loss can be accepted, as is the case today, in which each farm or cluster is connected to one link.

A very important consideration when dealing with a converter loss is the mismatch between time constants: The power reduction from wind generators due to overfrequency is achieved by mechanical means: Changing the turbine vane angles gives a reduction of 25% of nominal power per second or slightly better [2], whereas the overload time limits of HVDC VSC are dictated by the power electronic components (IGBTs): The limits are in the order of milliseconds for heavy overload, such as would occur upon loss of one converter in a system with only two links, if the dispatch had been done at 100% power in both.

One could be attracted by the idea of using the dc choppers on the HVDC links, but this would not help, since the choppers are in the dc side of the converters and would not alleviate their overload. Installing additional choppers on the offshore ac side would work, but this would require additional transformers, valves and resistor which would significantly add to the space and weight requirements on the platform. This would be quite expensive.

One can also be tempted to think that the VSC control could alleviate the situation by limiting the power until some generators are tripped, but this is not a solution. As there are no synchronous machines that can take the excess energy into their rotors, limiting the converter power would only send the excess energy elsewhere: to capacitors and cable shunt capacitances at first, by increasing their voltages, and then to arresters.

Tripping excess generation can be a solution, though; but only if the instantaneous overload on the remaining converters is low enough for them to have the capability to wait for decision-plus-breaker time. This means that the total generation in normal state will have to be carefully limited, especially when there are few HVDC links in parallel; the worst case being when there are only two, or if one is much larger than the other(s).

Studies can be performed off-line, well in advance, for the foreseeable operating conditions, considering the loss of each HVDC link, so as to define which limits to impose on the generation in normal state, and which specific generators to trip upon converter loss. The generators to trip may be kept by the control already in readiness, in different lists, for different scenarios, depending on which converter trips, so that the delay will be minimal.

A simple study could define the steady state generation so that no overload would occur at all on the remaining converters but this would be too conservative and cause excessive expenses.

To minimize the cost of non delivered generation the studies should include the permissible resulting overloads from the characteristics of the HVDC links.

Finally, and probably most important: Depending on the market conditions, limiting the generation may cause extra costs: In some markets, the payments to the generating entity are based on its available generation, and are not diminished if the generation has to be lowered because of transmission limits. Curtailing the total generation means that the difference will have to be paid by the pool without getting any energy in return. Integrating this cost along the 30~40 years of useful life can result in significant present value. So significant, in fact, that it may make parallelling unattractive.

# 7 Conclusions

Parallelling HVDC links on the offshore side so as to form a new ac system is possible. In some cases it may be desirable. To be able to do it, the operating principles have to be revised from those of isolated HVDC links and from those of normal ac systems: Special principles have to be defined.

The conditions needed to avoid catastrophic tripping will most likely impose economical consequences which may offset the possible advantages of parallelling.

# BIBLIOGRAPHY

[1] CIGRÉ Technical Brochure 370. “Integration of large scale wind generation using hvdc and power electronics”. Working Group B4.39. February 200

[2] “Requirements for Offshore Grid Connections in the Grid of TenneT TSO GmbH”, October 5th 2010

[3] L.H. Hansen, F. Blaabjerg, H.C., Christensen, U. LindHard, P.H. Madsen, K. Eskildsen, “Generators and Power Electronics Technology for Wind Turbines”, Paper presented at IECON’01, The 27th Annual Conference of the IEEE Industrial Electronics Society.