TWENTIES project

Final report
October 2013

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Transmitting wind

Transmission system operation with a large penetration of wind and other renewable electricity sources in electricity networks using innovative tools and integrated energy solutions (TWENTIES)

Final report

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INTRODUCTION: WHAT IS TWENTIES?

What is TWENTIES?

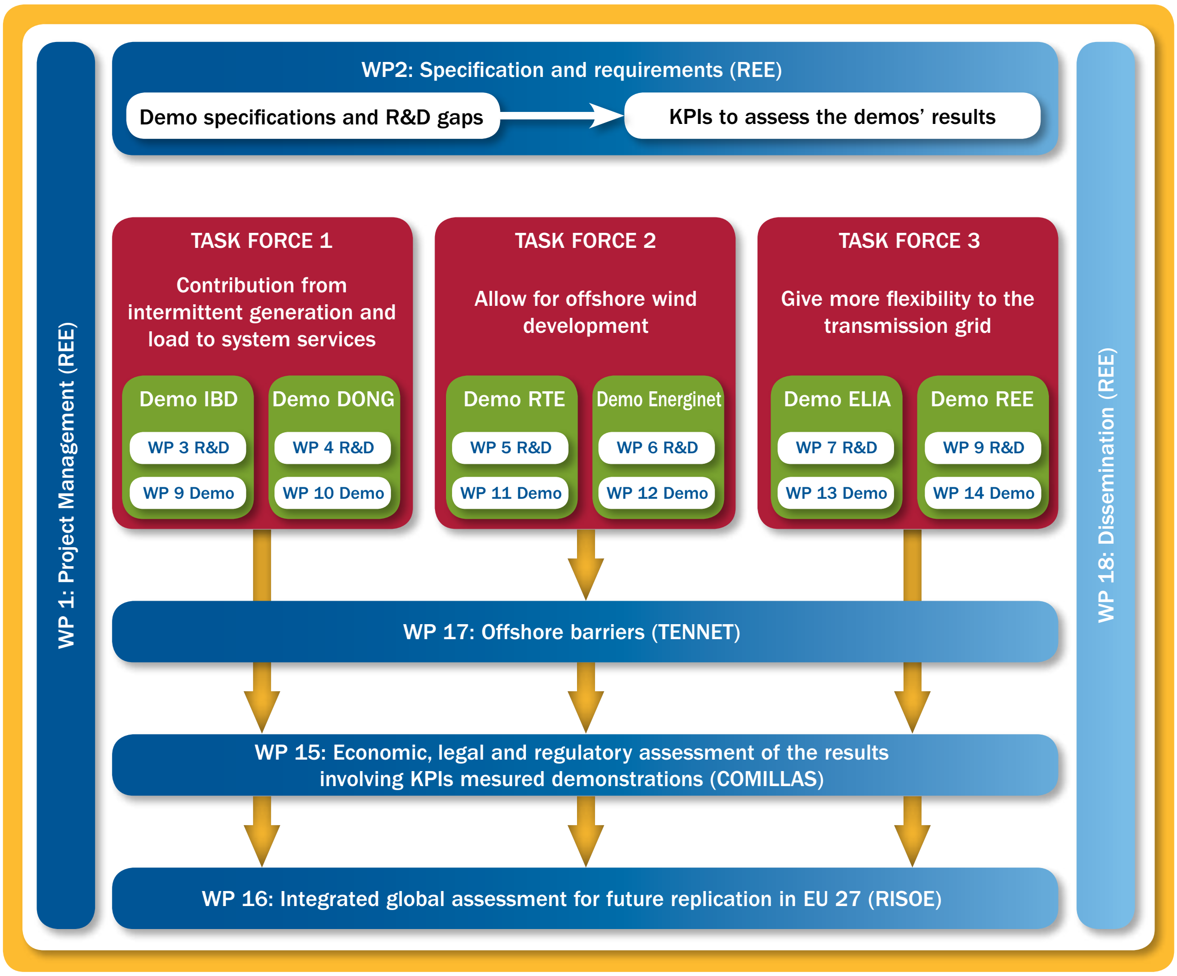
The EU-funded TWENTIES project - 'Transmission system operation with a large penetration of wind and other renewable electricity sources in electricity networks using innovative tools and integrated energy solutions' - coordinated by Spanish Transmission System Operator Red Eléctrica de España, was launched in April 2010.

The aim of the TWENTIES project is to advance the development and deployment of new technologies which facilitate the widespread integration of more onshore and offshore wind power into the European electricity system by 2020 and beyond.

TWENTIES is one of the largest renewable energy demonstration projects funded by the European Commission's Directorate-General for Energy under its seventh Framework Programme (FP7), with a total budget of over €56.8 million, and a European Commission contribution of close to €32 million. The TWENTIES project brings grid operators and wind energy operators together for the first time.

TWENTIES is organised around six large-scale demonstration projects grouped into three Task Forces, which aim to prove the benefits of new technologies. The six large-scale demonstrations are complemented by three work packages. One of the work packages focuses on the assessment of non-technology barriers to the development of a real offshore grid, and makes proposals for overcoming such barriers. The other two are related to the replicability and scalability at EU level of the results of the demonstration projects, based on their individual impact as well as the potential synergies between them.

FIGURE 1 TWENTIES PROJECT STRUCTURE



What did TWENTIES find out?

TWENTIES shows that Europe's energy infrastructure can be used a lot more efficiently than it currently is. The most significant findings include the following:

- Wind farms can provide wide area voltage control, and secondary frequency control services to the system;
- Virtual power plants enables reliable delivery of ancillary services, like voltage control and reserves, by intelligent control of distributed generation including wind farms and industrial consumption;
- A DC circuit breaker prototype was tested successfully;
- By applying 'high wind ride through control', reserve requirements are cut in half;
- By using Real Time Thermal Rating (RTTR) or Dynamic Line Rating (DLR) for measuring and forecasting overhead line capacity, 10% more flow in average can go through equipped overhead lines;
- By using the combined effect of DLR and power flow controlling devices to control the flows in the European grid, more wind in-feed can be integrated in the existing grid without jeopardizing the system security;
- By controlling flows by means of PSTs, HVDCs and FACTS, local congestions can be alleviated in a flexible manner. A smart control of a set of such devices enable getting even more out of the existing grids.

The key results:

Task Force 1: Contribution of variable generation and flexible load to system services

Demonstration project 1: System services provided by wind farms (SYSERWIND)

- Wind farms provided wide area voltage control, reducing voltage deviation from 9 kV to 0.7 kV;
- Wind farms can work in a coordinated way to provide secondary frequency control in the same way as conventional units;
- Secondary frequency control involves many challenges, including the need for very accurate wind forecasting in order to avoid curtailing large amounts of power;
- Wind farm voltage control leads to less wind curtailment and slightly lower overall system costs.

Demonstration project 2: Large-scale virtual power plant integration (DERINT)

- The virtual power plant - "Power Hub" - enables reliable delivery of ancillary services, like voltage control and reserves, by intelligent control of distributed generation including wind farms and industrial consumption;
- Power hub was able to optimise the output from the available resources in different units across different markets, deciding when most value would be generated;
- It is economically attractive to build virtual power plants. Power Hub can be replicated across Europe.
- Virtual power plants reduced marginal electricity prices by 0.25-0.4% and brought about lower total system costs in the day-ahead market in the Danish system;
- VPPs based on biomass and heat pumps could provide a 2.18% reduction in average electricity prices and a 3.46% reduction in CO_2 emissions in the German power system.

Task Force 2: Reliable offshore network and wind development

Demonstration project 3: Technical specifications towards offshore HVDC networks (DCGRID)

- A DC circuit breaker demonstrator was successfully tested, and innovative DC protection algorithms validated;
- Local controls were designed to enable various DC grids to accommodate wind power transmission and a large range of contingencies (including on the AC system) without any need for high-speed telecommunications, as demonstrated with the first DC grid mock-up (including physical cables and protection).

- New offshore grids allows local surpluses of wind power to be used elsewhere, reserve power to be held, and potentially cheap, low carbon power to be used instead of more expensive higher carbon fossil fuel plants.

Demonstration project 4: Management of offshore wind power in extreme high wind situations (STORM MANAGEMENT)

- Wind turbine energy output was increased in stormy conditions by using high wind ride through control, which took the cut-off point from wind speeds of 25 metres per second up to 32 metres per second;
- Use of high wind ride through control reduced the risk of power system instability and blackouts.

Task Force 3: Improvements in the flexibility of the transmission grid

Demonstration project 5: Network-enhanced flexibility (NETFLEX)

- By installing Ampacimon sensors that measure vibration to deduce the sag of the line, and forecasting capacities, TSOs can enjoy an average 10-15% more capacity out of overhead lines;
- By acting together, Power Flow Controlling devices (PFCs), like PSTs and HVDCs, can better distribute the flows over an entire area and unlock room for more wind power and exchanges;
- At the moment, the system damping is generally sufficient. Nevertheless, new means for controlling the damping must be identified to cope with high penetration of RES. Today, the damping of the system can be reliably predicted based on flows and injection.
- In order to achieve the same level of operational risk, the DLR forecaster can implement a more audacious policy because the smart controller enables compensating for over-estimations;
- The grid can be planned more boldly, i.e. higher capacities for the market and for wind, while delivering the same level of reliability.

Demonstration project 6: Improving the flexibility of the grid (FLEXGRID)

- Real-time monitoring of the temperature of the power cables allows over 10% more wind-generated power to be brought onto the transmission grid;
- Excess energy can be re-directed to lines with spare capacity in order to use the transmission capacity more efficiently, increasing the controllability and security of the grid and reducing the need for curtailments.

TWENTIES has held a number of dissemination events, some of them linked to the project General Assemblies and some in connection with other demonstration projects, and been present at several conferences and workshops in Europe.

The following pages present a brief summary of the most significant results obtained in each of the demonstrations, how the demonstration project worked, and an overview of the project work packages. A more detailed description of the work and the results achieved are available on the project site: www.twenties-project.eu.

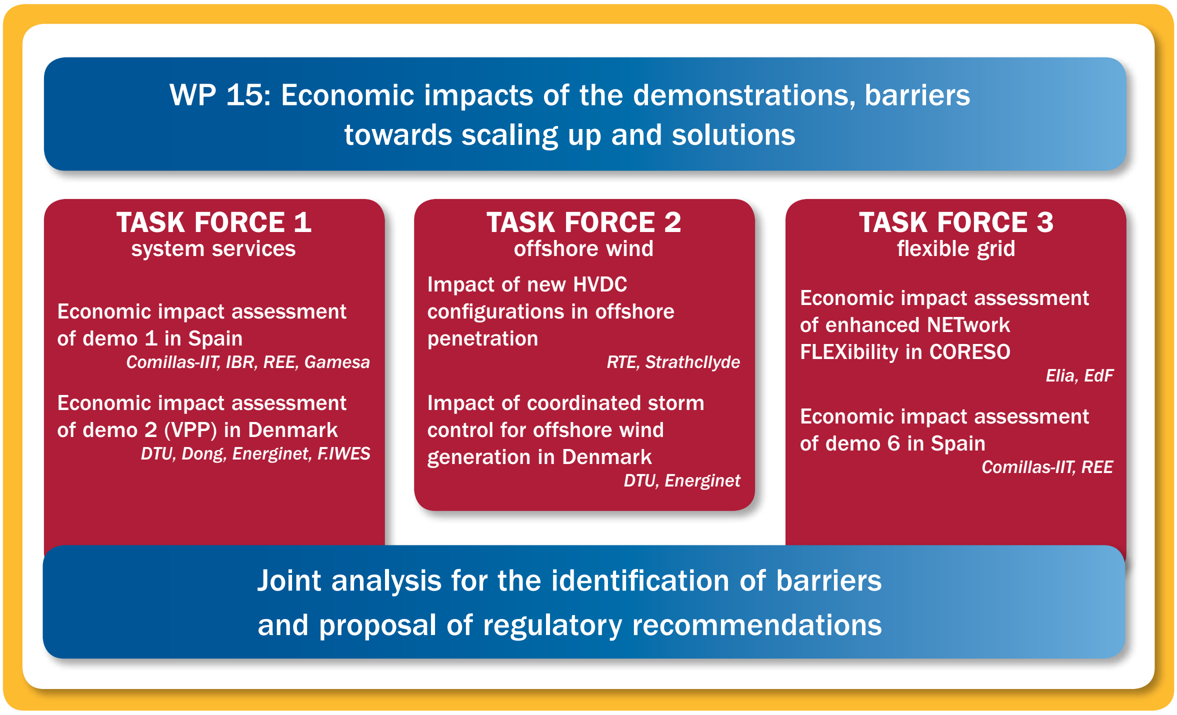
WORK PACKAGE 15 & 16 - A contribution to all task forces

Work Package 15

Introduction and background

Work Package ('WP') 15, 'Economic impacts of the demonstrations, barriers towards scaling up and solutions', relates to all the different elements of the TWENTIES project. Its goals are to assess the local economic and/or technological impact of each demonstration project ('demo'), to perform an analysis of the joint impact for all the demos in the same task force, to identify the barriers to scaling up the results, to propose regulatory and economic solutions to overcome the identified barriers, and to provide an analysis of the demos to be used in Work Package 16, which gives an EU-wide perspective of the larger technical and economic impact of the demos. The figure summarises the main activities developed in WP 15.

FIGURE 2.1 WP 15 - ECONOMIC IMPACTS OF THE DEMONSTRATIONS, BARRIERS TOWARDS SCALING UP AND SOLUTIONS



Results and conclusions

Despite the benefits of the innovative system management approaches and the novel technologies demonstrated in TWENTIES, there are still some regulatory barriers preventing relevant benefits from being realised. One important barrier relating to Task Force (TF) 1 and TF 2 is the current design of day-ahead, intraday and balancing services. Their rules were not defined to integrate high shares of intermittent renewable generation. Three elements of the market should be improved to favour a higher penetration of renewable generation: liquidity, flexibility and integration with other power systems' markets. Another major barrier to the development of offshore grids is the high investment needed, and cost allocation. To overcome this barrier, existing inter-Transmission System Operator (TSO) compensation mechanisms will need to be developed and joint support instruments and targeted EU funding need to be enhanced. The adoption of grid technologies such as those tested in TF 3 include economic and environmental criteria for assessing alternative solutions and the definition of standards for the use and control of these technologies. The latter is especially relevant when different TSO jurisdictions are affected, which will require agreement between the relevant TSOs.

Regulatory recommendations for TF 1

- Establishing market mechanisms for the procurement of system services and remuneration schemes based on cost-reflective prices;
- Defining markets for the procurement of balancing reserve capacity (where participants take the commitment of reserving capacity) and balancing energy (whereby the TSO balances the system based on the energy offers from reserve capacity providers and from other participants);
- Defining products that recognise the intrinsic characteristics of potential market participants such as renewable generators, load and storage units (shorter product lengths, gate-closure times closer to real-time);
- Imposing balancing responsibility on all market participants so that they are incentivised to "self-balance" instead of increasing the demand for balancing services, which in turn increases system costs;
- Defining imbalance prices that reflect the costs imposed on the system by imbalanced market parties so that they receive the incentives to be balanced.

Regulatory recommendations for TF 2

- Definition of clear targets for offshore generation beyond 2020 (2030-2050) agreed between the EU and its member countries as the main driver for offshore infrastructure development;
- Establishing a clear regulatory framework for offshore generation, including the harmonisation of support schemes or the introduction of flexible mechanisms such as joint schemes to reduce the distortions from national schemes;
- Creating mechanisms for the coordination of planning, development and operation of common offshore grid infrastructure, such as the creation of regional initiatives or organisations (e.g. the North Seas Countries' Offshore Grid Initiative - NSCOGI and Coreso[1]), the development of methodologies for coordinated transmission planning, ex-ante allocation of costs among infrastructure users;
- Developing a framework for grid infrastructure financing that acknowledges the particular financial needs of TSOs. In order to incentivise investors to finance complex projects, investment risks should be reduced and attractive remuneration established;
- Harmonising market designs and defining specific arrangements for offshore generation such as transmission capacity rights allocation, definition of bid areas and priority access for cross-border offshore assets.

Regulatory recommendations for TF 3

- Developing methodologies for coordinated transmission planning and creation of regional organisations such as Coreso;
- Harmonising grid codes (e.g. congestion management, priority access and renewable energy curtailment) for the operation of common infrastructure;
- Incentivising TSOs to invest in new and flexible grid technologies. National regulatory authorities (NRAs) should encourage TSOs to invest in R&D by defining cost-reflective network tariffs. Also, efficient costs of new technologies must be acknowledged by NRAs in order to reduce TSOs investment related risks.

[1] Coreso is an independent company checking and improving the security of supply level in Western Europe. Its goal is to help European TSOs by providing them with a comprehensive overview of electricity flows, complementary to their national focus (www.coreso.eu)

Work Package 16

Introduction and background

The purpose of WP 16 was to supplement WP 15's economic, legal and regulatory assessment of the demonstrations in the countries that host each one, giving an EU-wide perspective of the larger technical and economic impact. A major part of the work in WP 16 has focused on regions like the North Sea and large countries like Germany and France.

The main activities in WP 16 are summarised in Figure 2.2 below.

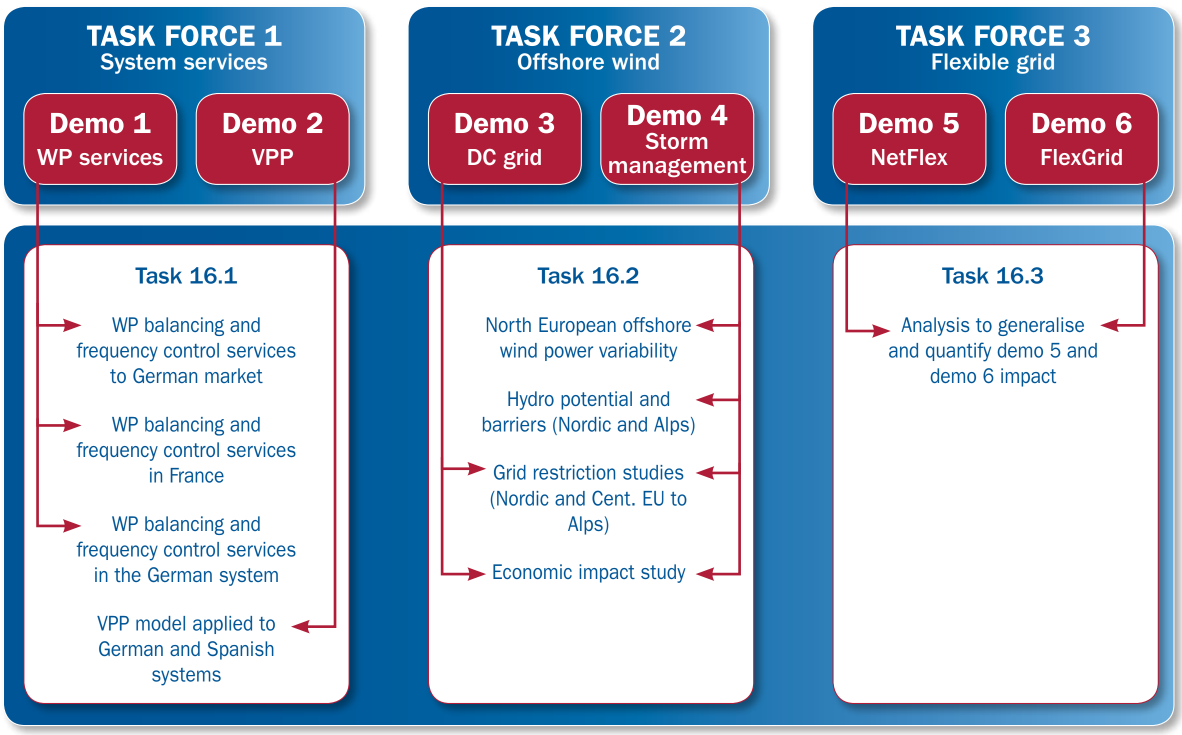
Results and conclusions

It has been shown that wind power plants and Virtual Power Plants can contribute to system services such as frequency control and voltage control. The impact will depend on regulatory rules and market structures.

The analyses of the impact of increased hydro capacity and offshore interconnections in North Europe show significant potential for enhancing the use of hydro power generation to balance wind power. The economic impact studies should be followed up by investment studies to quantify the cost of increasing hydro capacity of interconnectors as an alternative to construction of new plants and postponing the decommissioning of existing thermal power plants.

Analysis of the transmission system operators' (TSO) Alps hydro scenarios suggests that if wind capacity in the North Sea reaches its maximum potential, the hydro capacity in 2020 and in 2030 may not be well connected to the wind generation in the Central Western Europe (CWE) region and thus may not be able to fully exploit the increased wind generation. In such a case, the analysis suggests that the positive effect of grid extension alone may be higher than the further increase in hydro capacity. The simultaneous increase of the grid and hydro capacity may provide the greatest increase in social welfare benefits from the European electricity system. If the wind capacities do not increase after 2020, the potential Alpine hydro capacities in 2020 and 2030 can help integrate intermittent wind output into the European electricity system without additional transmission investments.

FIGURE 2.2 WP 16 - EU WIDE INTEGRATING ASSESSMENT OF DEMONSTRATION REPLICATION POTENTIAL



TASK FORCE 1 - Contribution of variable generation and flexible load to system services

Demonstration project 1 - System services provided by wind farms (SYSERWIND)

Main findings

- Wind farms provided wide-area voltage control in the transmission grid, reducing voltage deviation from 9 kV to 0.7 kV;
- Wind farms can operate in a coordinated fashion to provide secondary frequency control with similar technical performance as conventional units;
- Secondary frequency control involves many challenges, including the need for accurate wind forecasting in order to avoid curtailing large amounts of power;
- A large amount of energy has to be curtailed to provide the upwards power reserve service so it is not currently attractive from an economic perspective, unless market design changes are made.

Introduction and background

Currently, conventional generators provide key services to the electrical system that wind generators are not able to provide: voltage control in the transmission grid and secondary frequency control. As wind penetration increases, reducing the conventional generation's share of the power supply, it becomes more important for this technology to support the system with such services.

On alternating current (AC) systems, reactive power is used to control the voltage in different parts of the grid; when reactive power is injected the voltage increases and vice versa. The ability to perform this voltage control is of great importance for three main reasons:

1. The electrical equipment is designed to operate within a certain range, usually +/- 5% of the nominal voltage. A high voltage can damage equipment and low voltages make some elements perform poorly and even shorten their lifetime.
2. Reactive power flows cause losses.
3. The production of reactive power can limit a generator's capability to produce active power.

The dynamic nature of the electricity system implies that voltages are constantly evolving as inductive and capacitive elements are added and removed from the grid or active power transmission levels change. The dynamic control of the voltage in the transmission grid has been traditionally performed by conventional generators, while the reactive power control capabilities of the wind turbines have been used solely to optimise the losses in the medium voltage (MV) network of each wind farm.

Another important service provided by conventional generators is the secondary frequency control. In an AC system, mismatches between load and active power generation cause variations in the system frequency. If the load is larger than the generation the frequency drops and vice versa. This continuous balance is performed by a system known as Automatic Generation Control (AGC), which adjusts the power output of different generators, which are paid to provide this service, following the changes in the load. Due to the nature of wind, it is very difficult for wind generators to participate in this service because of the technical challenges, and the economic impact should also be specifically evaluated (cost-benefit comparison with other technologies).

TWENTIES Demo 1 aims to prove that wind generators are technically able to provide wide-area voltage control and secondary frequency control services.

Description of project

The first demonstration in TWENTIES faces the challenge of clustering 15 wind farms in the south of Spain adding up to 482 MW and connected to three different 400 kV nodes in the transmission grid (Tajo de la Encantada, Arcos de la Frontera, and Huéneja), in order to prove the ability of wind generation to provide services like wide-area voltage control and secondary frequency regulation to the system while minimizing the equipment modifications at wind farm level.

These objectives have been pursued by developing new controllers that have been installed in Iberdrola's and Red Eléctrica de España's control centres and the wind farms, which implement new strategies that make 240 wind turbines work in a coordinated way in order to control the voltage in a 400 kV AC corridor more than 350 kilometres long.

It has also been necessary to develop a very short term wind forecasting algorithm in order to provide a secondary frequency regulation band with the necessary precision. Most importantly, these tools are fully integrated into the system operation and the TSO tools.

The demonstration is divided into two main tests: a voltage control test and a secondary frequency control test. In the first case, all the TWENTIES wind farms control their reactive power generation and consumption in a coordinated fashion, thus modifying the voltages in the 400 kV nodes in a controlled way. Figure 3.1 shows the results from this part of the demonstration.

FIGURE 3.1 WIDE AREA VOLTAGE CONTROL TEST RESULTS

Source: Iberdrola

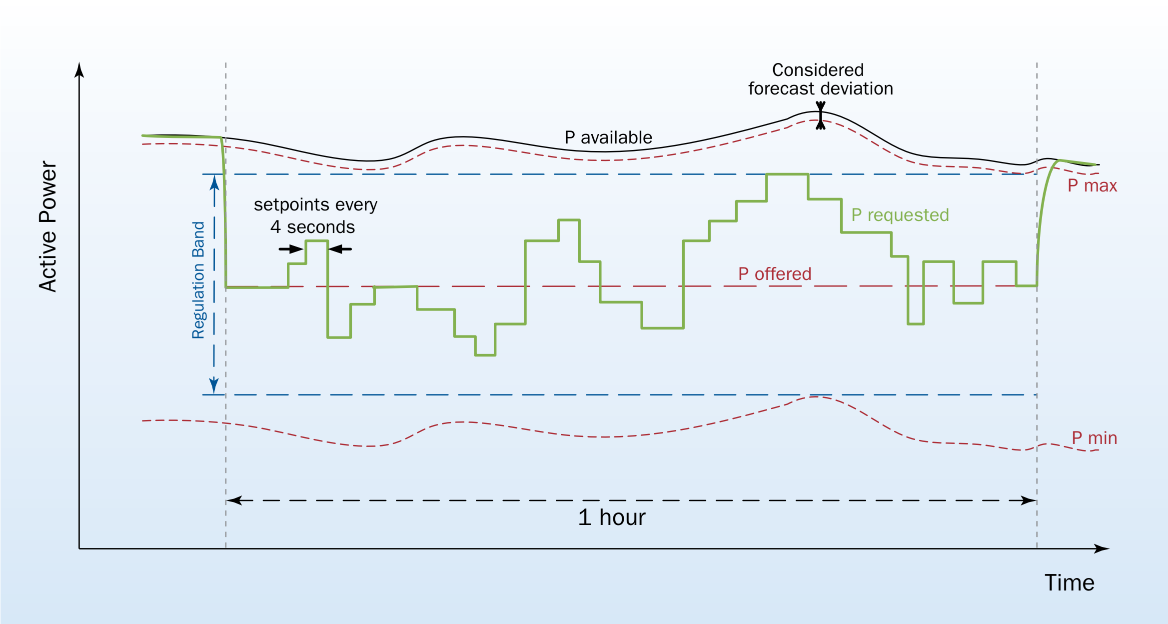
During the test wind conditions were very good, with high capacity factors (70% in Huéneja, 83% in Tajo de la Encantada and 97% in Arcos de la Frontera). The figure shows that initially the maximum voltage difference between the clusters was 9 kV and as soon as setpoints (i.e. the signals containing the requested voltage value) were received from the TSO to achieve a flat voltage profile the voltage levels in the clusters started to converge, reaching a minimum difference of 0.7 kV in the last part of the test. As soon as the voltage control was deactivated, 1.5 hours after the start of the test, the voltage levels rapidly diverged again.

Controlling the reactive power capabilities of the wind turbines meant taking into account the behaviour of the MV grid of the wind farms as well as other installations that were not part of the demonstration. They were connected to the same nodes, and the on-load tap changer of the transformers, which reacted to the modifications in the voltage profile.

For the second part of Demo 1 the active power provided by the 15 wind farms taking part in TWENTIES is controlled in a coordinated way in order to allow wind generators to provide secondary frequency control services. To provide this service the generators must curtail their active power output and provide a regulation band (both upper and lower) that has been agreed with the TSO. While the service is being provided the TSO sends setpoints corresponding to any point inside the band, and they will have to be followed by the generators.

Figure 3.2 depicts how the test works.

FIGURE 3.2 SECONDARY FREQUENCY CONTROL TEST



Fifteen minutes prior to the beginning of the demonstration the wind forecast system calculates the expected available active power for the following hour. The minimum value of this forecast, generated for all the wind farms, is used as the upper limit of the regulation band (it is necessary to use the minimum value, otherwise there is no guarantee that all the setpoints will be followed accurately). In order to avoid the uncertainties of the wind forecasting algorithms, this upper value is lowered in correspondence to the estimated forecast error.

It has been necessary to improve the wind algorithms to provide short time forecasts. The wind speeds can now be estimated for two hours fifteen minutes before each period begins.

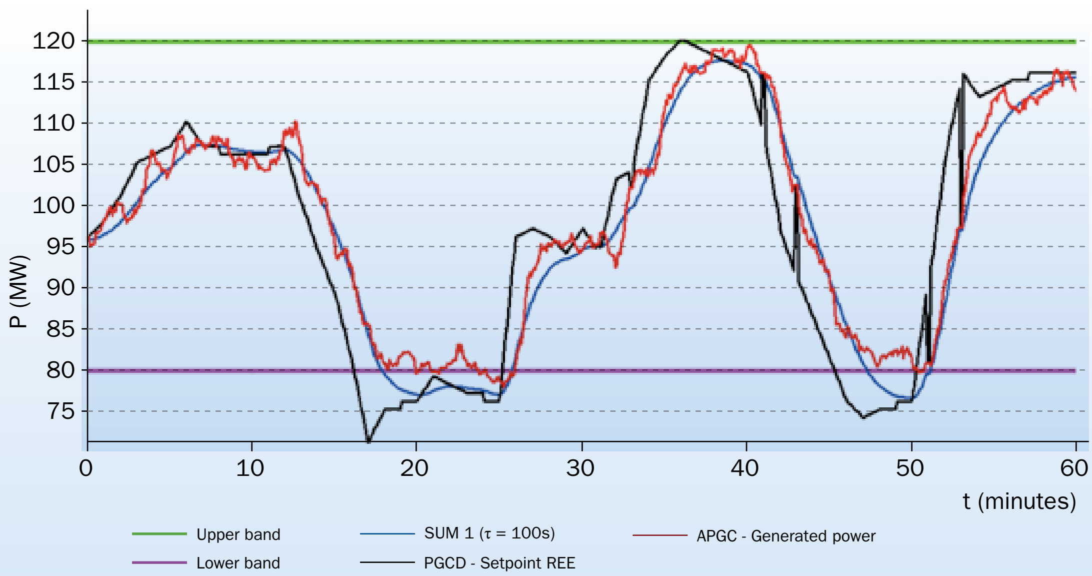
Likewise, the lower value of the regulation band is calculated taking into account the technical limitations of the wind turbines. When a wind turbine is regulating active power by means of changes in the pitch of its blades there is a lower limit in which the turbines stop. In the case of the generators used in this demonstration, this value is between 25% and 50% of the nominal power. The control in the demonstration avoids stopping generators because it implies that starting them again may take several minutes until it finds the wind direction and configures the pitch to provide the requested active power output.

Once the regulation band has been defined, an initial power output is selected. The clusters will maintain at this level until the TSO starts to send its setpoints. These setpoints, arriving every four seconds, are calculated by the TSO taking into account the time constant (τ) of the generators, with the aim of reaching a certain behaviour. Setpoints in Figure 3.2 (green line) are indeed calculated by taking into account the dynamic behaviour of wind farms. Higher steps in the line mean that wind farms will modify their output with a steeper slope. As a result of applying these setpoints, the desired real dynamic response is achieved.

The wind farms taking part in TWENTIES cover a very large area of southern Spain, and sometimes the meteorological conditions differ from one cluster to another, as was the case during the day this demonstration took place. Arcos de la Frontera and Tajo de la Encantada had enough wind, while the wind farms in Huéneja were producing at less than 1% of the installed power, which is far below the technical limitations of the machines to perform active power regulation. Despite this, the wind farms that were able to take part had enough power to deliver a +/- 20 MW band with an initial value of 100 MW.

The results are shown in Figure 3.3.

FIGURE 3.3 SECONDARY FREQUENCY CONTROL TEST RESULTS (THREE CLUSTERS)



Source: Iberdrola

For most of the time the power generation was between the setpoint from Red Eléctrica (black line) and the required response with a time constant of 100 seconds (blue line). The generated power mostly fell between the upper and lower band limits, even when the TSO sends setpoints outside these boundaries. This is the expected behaviour, the generators offer the band and always operate inside these margins.

In order to provide a regulation band with the sufficient reliability throughout the test, a very accurate and reliable forecast is needed. Other difficulties were the need to respond rapidly to the setpoints that the TSO sends every four seconds and controlling the pitch in all the wind turbines so that power generation reductions were achieved without stopping any of the machines, which would have slowed the overall response of the clusters.

Results and conclusions

General

- The hardware and software changes in the wind farms and control centres were kept to a minimum. This means that the CAPEX for delivering these ancillary services is reduced (around 100 - 150 k€ per 50 - 100 MW wind farm) and there is not a clear impact on the OPEX.

Wide-area voltage control test

- The wind farms grouped in a cluster are able to control the 400 kV voltage in the TSO's point of connection, according to the same operational procedure that is applied to conventional generation;
- A flat voltage profile in the 400 kV corridor has been successfully achieved, with voltage differences between controlled nodes as low as 0.7 kV;
- A minimum capacity factor (around 20%) is required to adequately control voltages;
- The algorithms are able to effectively compensate the losses in the cables and lines up to the connection point;
- Limitations in reactive power generation capacities in the wind generators translate into limitations in voltage control.

Secondary frequency control test

- Grouped wind farms are able to control their active power, in real time and in a coordinated way, according to the TSO's secondary frequency control requirements;
- The controllers are able to change their response time in the same way that conventional generation units do;
- The secondary frequency control test has shown good performance with high capacity factors, although further research is needed to show how the results would be affected by machines stopping due to low capacity factors;
- A large amount of energy has to be curtailed for providing the upwards power reserve service, so it is not currently economically attractive;
- The required energy curtailment is lower when more wind farms are grouped to provide the service and there is a shorter term forecast calculation. However, the amount of energy to be curtailed is still quite representative;
- The current secondary reserve market is a day-ahead one, and wind energy would need a short term market, almost in real time, or to offer this upwards reserve only once wind generation has been curtailed by technical constraints, or just offer the downwards reserve.

Demonstration project 2 - Large-scale virtual power plant integration (DERINT)

Main findings

The virtual power plant ‘Power Hub’ has delivered the key objectives of TWENTIES - supporting the integration of wind in the European energy system. It has done so by developing a new tool, a virtual power plant for system balancing.

Power Hub enables reliable delivery of ancillary services, like voltage control and reserves, by intelligent control of distributed generation including wind farms and industrial consumption.

Power Hub was able to optimise the output from the available resources in different units across different markets, deciding when most value would be generated.

It is economically attractive for all stakeholders to participate in virtual power plants. Power Hub can be replicated across Europe, although challenges include attracting and integrating industrial units to participate in a virtual power plant.

Another challenge was scaling up the virtual power plant on commercial terms in Denmark due to the Danish regulatory regime and market design. Similar challenges have been identified in Germany and Spain.

Introduction and background

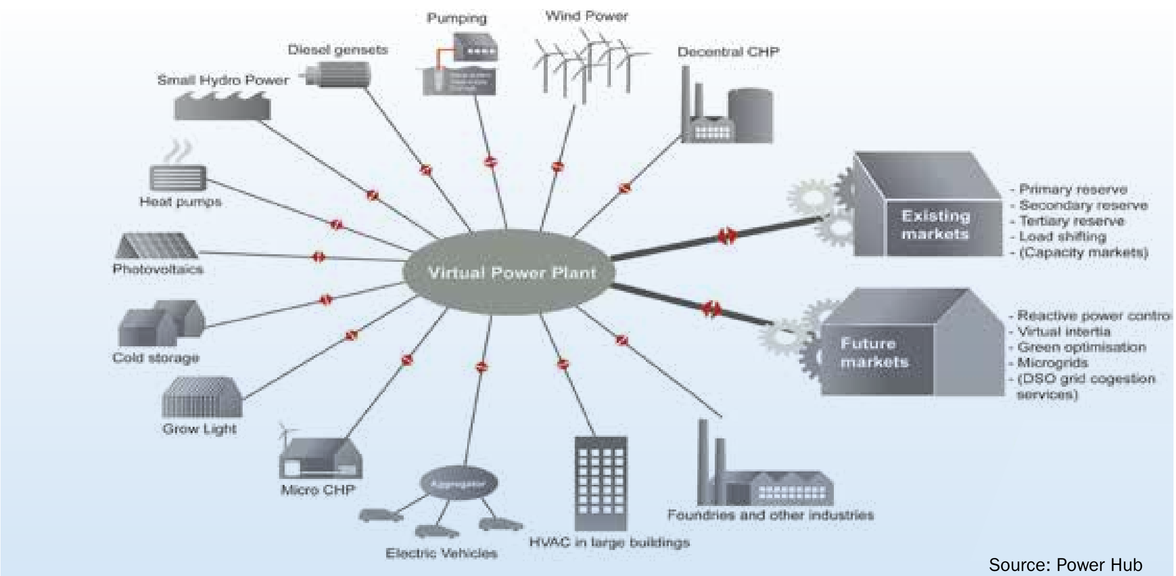
When an increasing share of energy is produced by renewable sources such as solar and wind, electric¬ity production can fluctuate significantly. In the future there will be a need for services that can help balance power systems in excess of what conventional assets can provide. Virtual power plants (VPPs) are one of the most promising new technologies that can deliver the necessary stabilising services. The goal of the second TWENTIES demonstration project was to show the full potential of the VPP technology.

Description of project

The demonstration project involved the development of a virtual power plant, named ’Power Hub’. Power Hub is an IT system that can manage both small power generators (such as small hydro power plants, indus¬trial combined heat and power plants (CHP) or emer¬gency generation sets) and power consuming units (such as pumps in waste water treatment, grow light in greenhouses, cooling in cold storages).

Power Hub’s main task is to ensure that all units are used optimally for both the electrical system and the unit owner.

FIGURE 3.4 THE VIRTUAL POWER PLANT



Source: Power Hub

When the units are used optimally, they are able to serve their primary purpose and to provide the services required by a future low carbon energy system. For example, pumping water can be stopped or started in a matter of seconds if the power system needs it. Similarly a small hydroelectric plant could gain access through Power Hub to provide services which stabilise the frequency of the power system, which would otherwise be too complex to deliver.

The virtual power plant (VPP) demonstration was set up in Denmark on fully commercial terms. This means that the VPP delivers services to the Danish power system based on the controlled units on a daily basis. It also means that the VPP only pays the unit owners a share of what can be earned from the portfolio of units in the existing markets.

Building a VPP covers a range of tasks, which fall into three main groups:

1. Building the conceptual solution, including the IT platform;
2. Reaching an agreement with the unit owner and installing unit controls;
3. Running the daily operation, trading energy and flexibility in the markets and delivering services by optimising the units.

Results and conclusions

Research shows flexibility in distributed energy resources is key to balancing the future energy system. Flexibility exists in many forms and has different uses in system balancing ranging from fast sub-second ramping, to hour-long reserves. In the future energy system the need for flexibility will be even greater than today, due to the fast development of wind power production all over Europe. The question will be how to mobilise flexibility rather than whether there will be enough flexibility in the energy system. The importance of sustainable business models encompassing all stakeholders will be clear.

Mobilisation of distributed flexibility is the core solution

TWENTIES Demo 2 has documented both the availability of flexibility in distributed energy resources ('DERs'), as well as the feasibility of mobilising the flexibility for system support on commercial terms acting through existing energy and reserves markets. The ability of Power Hub to integrate different energy producing and consuming technologies has been proven. Testing utilisation strategies based on marketing of energy and flexibility in existing Danish markets has produced compelling results. Even a small portfolio of assets can be competitive to existing resources participating in existing reserves markets, which means a VPP could be an efficient tool for utilising flexibility in DERs.

A number of different mobilisation strategies, business models and processes have been tested throughout TWENTIES. The key challenges identified in mobilising DER flexibility are related to the mobilisation process itself and to existing barriers in current market design and regulation. The latter are not developed with the challenges to the future energy system and with technologies like the VPP in mind.

Most DER owners are not aware of the potential economic value of flexible power production and consumption. Mobilising flexibility often involves time consuming efforts to create the necessary awareness among them, explaining the potential economic value as well as the value of contributing to the greening of the energy system. The most important driver for DER owners is by far economic value.

Because of the high mobilisation cost it is important to establish the total value of flexibility in each asset. The value of flexibility not only depends on the size of the unit in terms of MW regulation capability, but also on factors like response time, duration of up/down regulated level and regulation cycle frequency. The value is maximised with respect to the primary purpose of the assets and determined by the flexibility in the business process in which the asset operates. Hence real flexibility will often be less than the technical flexibility of the asset itself. In case of consumption assets, the size of flexible consumption and how well it fits into the existing technical requirements for ancillary services poses real challenges to mobilisation. Once the quality of flexibility is established, actual mobilisation depends on the cost of accessing flexibility, which often requires modification to asset controls or integration to third party control systems. Collaborating with third party aggregators/integrators has proved to be a way to drive down mobilisation costs and to integrate flexibility, which might otherwise be inaccessible to the VPP.

In TWENTIES, the Power Hub team approached more than 100 DER owners. Companies from many industries have agreed to participate in the VPP demonstration on commercial terms with a total of 47 DERs. Power Hub delivered real economic value to these customers. For generation assets the value is created bringing them into new markets, by optimising their production according to price forecast and automating relevant operations, for example scheduling and activation. For consumption assets the value creation comes from scheduling consumption according to price forecast (load shifting) and from delivering ancillary services, which in most cases is a totally new opportunity for the DER owner.

The capabilities of a successful VPP

The versatility of the VPP is crucial to success. Power Hub has demonstrated the technical capability to integrate and utilise both consumption and production assets and to optimise combined flexibility across both types simultaneously. However the current mandatory 1:1 relationship between the power contract and the balance responsibility on an installation represents a strong barrier to exploiting consumption based flexibility for ancillary services in Denmark. This regulation has limited Power Hub to approaching only DONG Energy power customers in Denmark for commercial operation of their flexibility. Customers with another retailer must change to DONG Energy in order to be integrated into Power Hub, but they are often tied into contracts runs over several years. In practice the VPP has not been able to attract customers without an existing power contract with DONG Energy.

Technical demonstrations

A number of technical demonstrations have been carried out to show the full capabilities of the VPP.

Power Hub can deliver ancillary services by controlling these Vestas wind turbines

In TWENTIES Demonstration 2 it has been crucial to demonstrate wind energy not only to be a challenge to the future energy system, but also an integral part of the solution. Power Hub has shown wind turbine generators ('WTGs') to be capable of delivering all required balancing services compliant with the technical specifications from the TSOs. However, the costs of reserve provisions from WTGs are highly dependent on direction of control under the current support regimes throughout Europe. In order to provide up-regulation, the WTGs have to run down-regulated (not at their maximum possible production). Under the current Danish support regime it is economically unattractive, because the feed-in payment for the curtailed production is deferred. On the other hand down-regulation through curtailment in case of excess energy production from WTGs exists in Denmark both as a TSO controlled mechanism and as a market-based incentive, because prices are allowed to become negative, causing WTG operators to shut down the farms.

In addition to the common balancing services Power Hub has proven to be capable of delivering a broader portfolio of balancing services, some of which are mandatory for specific types of production assets and some required in certain system setups. It is anticipated that these types of services will be traded on open liquid markets in the future with an energy system based primarily on renewable energy production.

The demonstrations in TWENTIES have shown that Power Hub is capable of delivering services such as reactive power and fast frequency demand response, as well as other services not yet managed through markets.

Power Hub is able to deliver reactive power by controlling emergency gensets

The Faroe Islands have decided to increase wind power from 5% in 2012 to 25% in 2014

Reactive power sources are needed in the power system to maintain the right voltage. A voltage collapse will in the worst cases lead to a collapse of the power system. Today reactive power is primarily provided by conventional power plants, which are required to run even when WTGs cover the entire load in the system. Power Hub is able to control DERs which can supply reactive power to the power system. Power Hub can provide automatic reactive power control as well as manually activated reactive power control.

Power Hub is able to deliver fast frequency demand response (‘FFDR’). The Faroe Islands have some of the world’s best wind resources, but they have a small and vulnerable power system with a high number of blackouts compared to continental Europe. The islands only have a few power plants, no interconnectors to other countries and harsh weather conditions with frequent storms. It is one of the most difficult places in the world to integrate large amounts of intermittent renewable energy. Despite these circumstances the Faroe Islands have chosen to pursue a green transformation of the energy system and in order to improve security of supply, Power Hub has been introduced. In case of failure at a power plant or a sudden drop in the wind power generation, Power Hub can compensate within less than a second by reducing or stopping electricity consumption from three industrial sites. This will help avoid blackouts and give the remaining power plants the short time they need to increase power production to re-establish balance between power consumption and production.

This Power Hub solution is not only relevant to the Faroe Islands. A majority of islands throughout EU have plans for moving towards a more sustainable energy future that include ambitious goals for the integration of renewable energy sources. In that sense there is a significant “market” for solutions like Power Hub, which supports islands, in achieving their renewable energy goals. The TSO’s of larger power systems on islands like Ireland and UK consider inertia a future issue, as wind power production rises. New solutions may be needed and FFDR is one option.

TWENTIES Demonstration 2 has shown how VPP technology can support the integration of an increased share of intermittent renewable energy in the European power system. The demonstration has been conducted by developing an advanced VPP that operates in Denmark on commercial terms, active in the ancillary services and power markets on a daily basis. The project has developed a unique VPP with extensive capabilities combined in a single solution. This makes it possible to fully exploit the industrial flexibility and deliver a large variety of services beneficial to the future low carbon power system. Demonstration 2 has come far towards its vision: ”to show the full potential of virtual power plant technology”.

Work Package 15 - Economic impacts of the demonstration projects, barriers to scaling up and solutions

Main findings

- TWENTIES has overcome a major technical barrier preventing better use of wind generation relating to the capability of wind farms to provide frequency and voltage control.
- The analysis of the 2020 scenario for Spain shows that active power control by wind farms could reduce system operation costs by 1.1%. This reduction could be greater under conditions such as higher levels of wind generation and low installed power of flexible generation (as pumped-storage units).
- The analysis of voltage control by wind farms shows that wind penetration will not be limited because of voltage issues.
- VPP in the Danish system can decrease costs in the European power system. With the predicted scenario for 2030 (400 MW cold storage and 300,000 electrical vehicles), the estimated cost savings in the day-ahead market are 27 M€/year, and net balancing costs 3.4 M€/year. The reduction in wind curtailment due to the VPP is estimated at 18 GWh/year.

Work Package contribution

The economic impact of having wind farms in Spain provide active power control in 2020 was assessed by comparing two cases: a) wind farms do not provide active power control, and b) wind farms provide active power control. The results show that the provision of active power control by wind generators in Spain would reduce the need for committing extra conventional generation to comply with reserve requirements. This would avoid wind curtailments and slightly reduce system operation costs. The latter could be reduced by 1.1%, although the market share of wind generation and CO_2 emissions are barely affected. It is important to note that this cost reduction cannot be interpreted as renewable energy integration costs.

Most of the cost savings are explained by using wind generation to provide downward reserve instead of conventional thermal generation. In case b (wind farms provide active power control), downward reserve provided by wind generators accounts for 11.8% of total down reserve requirements. These reserves are provided during off peak hours, where thermal units are operated close to their minimum stable loads and hydro plants close to the run of river output.

The advantage of being able to provide active power control by wind farms is more marked where wind generation spillages are higher. In the nominal scenario wind generation capacity is 34,820 MW. Assuming an increase of 20% of wind generation capacity (38,302 MW) the provision of active power control by wind farms has a higher impact on cost savings (6.45%), reducing wind generation spillages and carbon emissions. A sensibility analysis in this study indicates that the economic impact is greater on systems with a high share of wind power capacity, low share of flexible pumping-storage facilities, and where reserve constraints influence the resulting generation scheduling.

The study demonstrated that in most cases wind penetration will not be limited for voltage reasons. Voltage control by wind farms causes a slight rise in active power loss in the wind farm grid. This could be reduced by developing an optimal voltage control strategy.

One important conclusion from the VPP assessment in Denmark is that even when treated solely as a demand-response unit, the VPP technologies have cut overall system costs and increased revenues. With the scenario for VPPs in 2030 consisting of 400 MW cold storage and 300,000 electrical vehicles (2,800 MW), the benefit of the VPP was estimated at 27 M€/y cost savings in the day-ahead, based on the WILMAR (Wind Power Integration in Liberalised Markets model) simulations. Additionally, the net balancing cost of the hour-ahead balancing performed by the Danish TSO is estimated to be reduced by 3.4 M€/y, so the total savings are approximately 30 M€/y. Other benefits of the VPP, such as savings in real time balancing and voltage control, may make the VPP even more profitable.

Another important finding from the WILMAR simulation is mixed results of the VPP in terms of its impact on CO_2 emissions, as they depend on the base-load fuel type. Finally, the wind shedding was reduced because of the VPP. This was expected, as the VPP was acting as a demand-response system. The total reduction in wind curtailment due to the VPP is estimated at 18 GWh/year.

Work Package 16 - EU-wide assessment of the demonstration projects' replication potential

Main findings

- It is socio-economically feasible to have wind power contribute to system frequency control in limited periods (Demo 1);
- Wind power could generate cost reductions in the secondary control reserve market of up to 24% with 99.99% reliability in Germany (Demo 1);
- VPPs based on biomass and heat pumps provide a 2.18% reduction in average electricity prices and a 3.46% reduction in CO_2 emissions from the German power system (Demo 2).

Work Package contribution

The potential for using wind power in frequency control in Germany and France was assessed, as was the economic impact of using wind power in secondary frequency control in Spain (Demo 1). In general, the results show that it is socio-economically feasible to have wind power contribute to system frequency control in limited periods, although this implies that wind power production will be less than it could have been in those periods.

The German study concludes that in the right conditions, wind power could generate cost reductions in the secondary control reserve market of up to 24% with 99.99% reliability. The full potential will be deployed if wind turbines decided only to bid for down-regulation reserve products (that is, not offering to increase but only to reduce power output). Bidding for up-regulation reserve products under the current cost structure is not beneficial for wind farms.

Using a supply and demand model, the French 2020 case study concludes that less than 2% of the total required frequency control volume will be provided by wind power. This contribution corresponds to a total cost saving of 2.3 M€/year.

The potential for using wind power in voltage control was assessed in three wind power plants in Willich, Germany (Demonstration project 1). The cost of using wind power in voltage control varies between 0.022 €/kVarh (kVarh = kilo Volt amps reactive power in one hour) and 0.0393 €/kVarh, depending on the different wind power plant grid layouts.

The potential for using Virtual Power Plant (VPP) in frequency control in Germany was assessed as an upscaling of Demo 2, and supplementing the VPP upscaling in Denmark done in WP 15. The conclusion is that VPPs in Germany, based on biomass and heat pumps, could provide a 2.18% reduction in average electricity prices and a 3.46% reduction in CO_2 emissions from the country's power system.

TASK FORCE 2 - Reliable offshore network and wind development

Demonstration project 3 - Technical specifications towards offshore HVDC networks (DCGRID)

Main findings

- DC Circuit Breaker (DCCB): The technical feasibility of an innovative DCCB was proven through successful medium-voltage power tests witnessed by an independent observer: current conduction in closed state, fast current interruption, voltage withstand in open state. The assembly of the high-voltage DCCB demonstrator and new power tests are expected by end 2013;
- The first meshed Direct Current Grid (DCG) mock-up (with 15 km cables and protection devices): a five-terminal DCG using hardware-in-the-loop facility on actual and simulated equipment was designed and assembled. It proved the viability and robustness of various DCG converter controls, including coordinated control;
- Innovative DC fault detection algorithms: DC fault detection algorithms have been designed and validated on the DCG mock-up with physical cables to illustrate new principles for a DC protection plan;
- Autonomous power flow control (wind power transfer and AC interconnection): DCG topologies (such as the « backbones ») make it possible to design dedicated autonomous controls for onshore converters to transfer power according to a predefined behaviour (wind power mitigation or not, with possible AC inter-area power exchange), thus accommodating for wind intermittency in a communication free system;
- Partial power flow control and wind spillage: Some complex DCG structures (possibly resulting from existing grid extensions) may result in partial power flow control, due to their complex structure. The principles of a simple Power Flow Control (PFC) device were analysed, resulting in a gain in power flow flexibility and significant savings on wind spillage;
- DC power flow control for AC network security: The principles of preventive strategies to reduce potential AC congestions by shifting DC power injections has been demonstrated using algorithms based on a risk-based control strategy to minimize the overall high current risk while minimizing the redispatching costs;
- Ancillary services : In addition to voltage support for the AC onshore power system, primary frequency control capability and inertia emulation can be provided (like conventional AC generators) with supplementary autonomous controls using DC voltage deviations. Other services can be provided on a case by case basis, such as Power Oscillation Damping;
- Fault Ride-Through (FRT): The capability to maintain the DC voltage during an AC contingency or the loss of an onshore converter could be provided by either using a DC chopper resistor, or relying on coordinated cascaded controls for the offshore converters and wind turbines. However, the combination of both approaches would be highly recommended;
- AC protection: Protection coordination is required at the interface between the DCG and the AC onshore network to cope with potential malfunction of relay protections (under-reach issue). In addition, System Protection Scheme (SPS) can play an important role to detect a particular system condition causing unusual stress, and to take predetermined action to counteract instability;
- Technological survey: Voltage Source Converter (VSC) is obviously the most promising DC technology for offshore DCGs. Simulations of various contingencies prove that some types of VSC (currently under development) will be best suited to build an offshore DCG (unlike wind turbines, for which no preferred technology arose);
- Economic drivers for the offshore DCG: Global cost benefit comparisons between radial connections and DCG schemes using various sets of parameters (like the cost of DCCB and cable capacities) reveal that there is no clear advantage of one connection scheme compared to others. DCGs are more costly but also provide added benefits for operation and remain competitive overall. At the 2020 or 2030 horizon, other uncertainties like regulation criteria or the cost of CO_2 emissions will also play a significant role in the balance.

Introduction and background

Wind energy is already a mainstay of clean power generation in Europe, with over 100 GW of capacity installed so far, and another 120 GW anticipated by 2020 according to various analysts. Much of this capacity is expected to be installed offshore, as it is a windier and steadier source compared to onshore wind energy.

High-voltage direct current (HVDC) transmission technology provides the platform that can be used to enable massive integration of offshore wind farms into AC onshore networks with minimum losses and increased flexibility over power control. Although no Direct Current Grids (DCG) are operational yet, such grids are widely investigated for integration of multiple offshore wind farms dispersed over wide areas into AC onshore networks. In addition to optimisation of AC and DC transmission infrastructures, and potential improvement of reliability and security of supply, DCG are expected to provide additional functionalities and meet some requirements: wind power transfer function (including smoothing of wind power fluctuations); interconnection function (i.e. use of the DCG to exchange power between AC zones); ancillary services (e.g. voltage support, frequency support to onshore AC grids, etc.). Finally, security assessment must be specifically addressed to prevent instabilities and cascading outages of the DCG, but also any adverse effect on the mainland AC network.

In spite of those potential benefits, no DCG currently exists, as major barriers still remain. The objective of the "DC Grid" demo is to clarify and overcome some significant barriers, either technological or economic: what controls should be implemented to operate an offshore DCG in a flexible yet robust way (both for the DCG itself, but also the AC network)? Are such controls compatible with the provision of ancillary services for the onshore power system? How to protect the DCG, for which no DC Circuit Breaker (DCCB) is currently available on the market? What new detection algorithms have to be specifically designed, since those used in AC cannot operate on a DCG? What is the economic viability of a DCG (and how can it be influenced?) compared to point-to-point DC connections?

Those questions were addressed within the DEMO 3 of TWENTIES, shedding new light on offshore DCGs thanks to major achievements (DCCB demonstrator, and the first meshed DCG mock-up with physical cables and protection devices), and new controls and methodologies.

Description of project

The challenges associated with DCGs connecting offshore wind farms are addressed in DEMO 3 through two work packages:

Work Package 5 (WP 5) is responsible for Research and Development tasks, including: the control and protection strategies of DCGs (for different grid structures) including autonomous power flow controls, ancillary services provided to the AC network and the Fault Ride-Through capability; the impact of the DCG on the AC protections; the economic drivers for the offshore DCG; reliability assessment of different DCG structures. This achievement is the result of a joint effort of WP 5 partners: RTE, as Work Package leader, INESC Porto, RSE, University of Strathclyde and UCD.

Work Package 11 (WP 11) gathers RTE (as Work Package leader) and Alstom Grid in contributing to the realisation of a key demonstrator: a DCCB demonstrator, designed and assembled by Alstom Grid, was successfully tested for medium-voltage as a proof of concept, while a high-voltage version is about to be tested (results expected by end 2013). In addition, the first meshed DCG mock-up (with 15 km cables and protection devices) was realized in Université de Lille (as sub-contractor for RTE) to prove the effectiveness and robustness of various control algorithms, both in normal operation and during contingencies. This mock-up was also used to validate innovative DC fault detection algorithms elaborated by G2eLab in Grenoble (as sub-contractor for RTE).

Results and conclusions

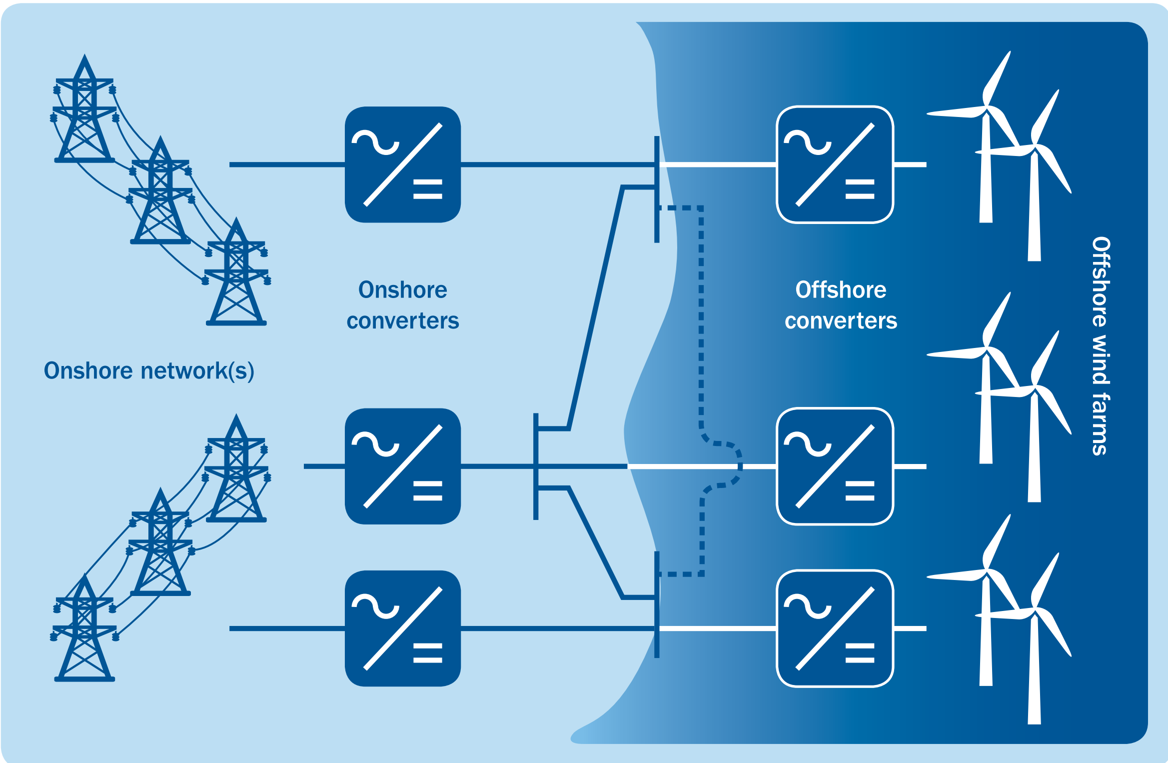
The DEMO 3 activities provided and demonstrated key building blocks for designing future HVDC networks which can be securely operated and integrated into existing AC systems. Investigations covered a significant range of security related issues, from the stable and reliable steady-state operation to the detection, clearing of and recovery from large perturbations like DC faults. The need and requirements for specific equipment and systems like master DCG controllers, DCCBs and associated protections schemes were characterized in simulations and through a laboratory test mock-up. Some classes of these requirements proved to be achievable using innovative DC technologies, as demonstrated through the test of a large scale DCCB demonstrator, and through operations on the first meshed DCG mock-up with physical cables and protection devices. Finally, the benefits and impacts of meshed DCGs were studied in the context of the North Sea area, in comparison with the current approach of radial connection of wind farms.

Considering that future offshore DCGs are likely to be built stepwise, the DEMO 3 activities distinguished three stages beyond radial connection of wind farms:

A first stage with small backbone-shaped DCGs can be readily constructed and extended

Such DCG layout (Figure 4.1) is feasible using currently available technologies, without specific equipment or systems like DCCBs or master DCG controllers.

FIGURE 4.1 TREE-LIKE (PLAIN LINES) AND MESHED (PLAIN AND DASHED LINES) DC BACKBONE EXAMPLES



Source: RTE

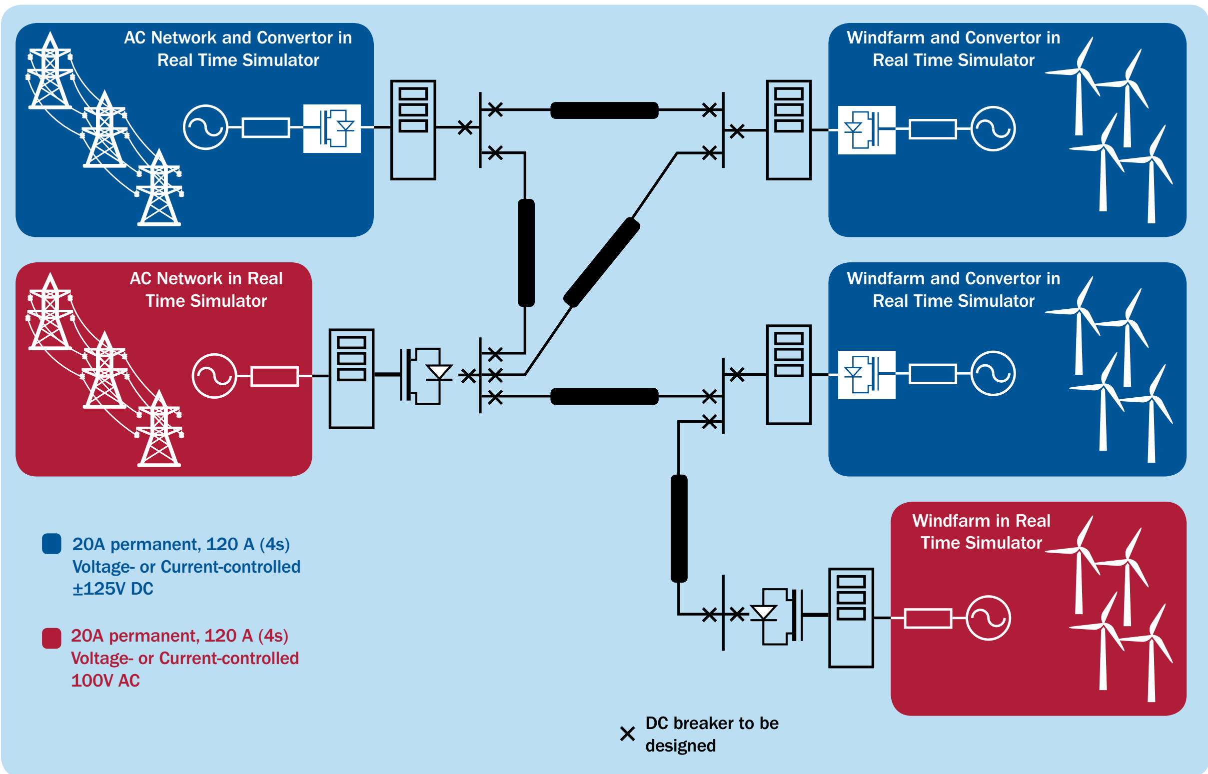
Autonomous controls for both the DCG converters and the offshore wind turbines were exhibited, which demonstrated that flexible power flow control in normal and disturbed conditions, ancillary services provided to the AC mainland network (voltage support, frequency control, Power System Stabilizer), and Fault Ride-Through capacity can be provided by such DCGs using local measurements only.

Fault clearance would then involve de-energizing the complete network from the onshore AC grid. Therefore the maximum power indeed from these networks must remain below acceptable values for such events, for example a few GW (depending on the primary reserve of the synchronous zone it connects).

An intermediate stage with simple meshed networks by 2020

Specific equipment or systems such as a master DCG controller would be required for such DCG, in addition to controls for the backbone structures. To establish these requirements and assess the operation of such networks, a representative network topology with five VSC terminals was used in simulation. In a second stage, the various controls embedded in the converters (master-slave, voltage droop, and coordinated control) were experimentally validated, using a scaled down five-terminal mock-up (Figure 4.2).

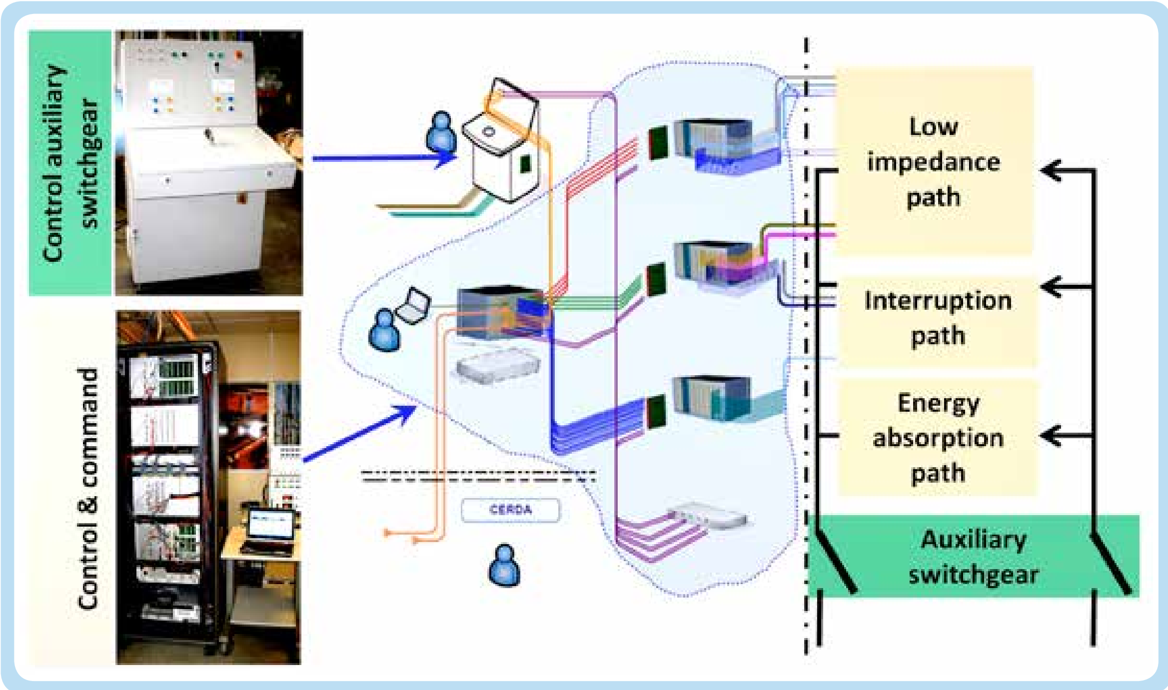
FIGURE 4.2 DCG MOCK-UP USING HARDWARE-IN-THE-LOOP (HIL) ON BOTH ACTUAL AND SIMULATED EQUIPMENT



Source: RTE

In case of a DC fault, the rate of rise and amplitude of the fault current are dramatic. Therefore, a protection system based on DCCBs is required to selectively detect and clear DC faults, as the loss of the complete DCG would not be acceptable. Three different classes of requirements were identified for the duty of DCCBs, depending on the ratings of the grid, but also the portions of the grid to protect. Two of them are met by the performance of the fast switch-type DCCB demonstrator (Figure 4.3) which was designed to meet their stringent speed requirements at acceptable cost, as witnessed by an independent observer and the EC Technical Reviewer.

FIGURE 4.3: DCCB DEMONSTRATOR ARCHITECTURE



Source: Alstom

Fault clearing time constraints also required the development of selective and very rapid protection schemes using optical fibres. Based on differential overcurrent relays, this was shown to be effective for cable distances no longer than about 200 km. It was validated experimentally on the DCG mock-up, where opening orders are sent in less than three milliseconds.

A final stage with complex meshed DCGs (by 2030 or later)

Secure operation cannot be yet guaranteed for this kind of grid given currently foreseen technological advances.

Economic analysis focused on comparing possible DC topologies (radial, point-to-point interconnectors, multiterminal, or meshed) in line with the development of offshore wind generation in the North Sea, based on the long-term planning methods used by European TSOs. It was quantitatively established that DCGs use underwater cable capacities more effectively than radial connection schemes to feed offshore wind power back to the continent, with the additional benefit of interconnecting energy production areas at the European scale. The DCG can also implement beneficial functions for operating the onshore AC grids connected to it, which were not assessed in the framework of the economic study: improved AC security margins through appropriate power injections via the onshore DCG terminals; ancillary services like voltage control, frequency support, synthetic inertia or damping of inter-area oscillations; black start restoration of the AC system from the offshore grid.

Global cost benefit comparisons between radial connection and DCG schemes were carried out while varying parameters such as cable capacity or the cost of CO_2 emissions and new DC technology. The main factors of influence, namely the cost of DC technology (especially DCCB) and the apparent merit order of conventional generation, have a large impact on the expected benefits of a DCG. From this analysis there is no clear advantage or disadvantage between the studied schemes. Grid schemes are more costly in terms of investment but provide added benefits for operation and remain competitive overall. At the 2020 or 2030 horizon, other uncertainties like regulation criteria on structural adequacy of the European generation mix could also play a significant role in the balance.

Recommendations

The TWENTIES DEMO 3 activities could be complemented by future testing of a low-scale DCG demonstrator, focusing on interoperability of multi-vendor components (including innovative VSC converters such as full-bridge topology), as a necessary step toward future standardization. This should also permit to test available DCCB components in real conditions (integrating the full protection chain, from detection to complete fault isolation).

In addition to such a demonstrator, further real-time simulations are required to include an AC network, the DCG and wind farms, for time scales ranging from µs to seconds in order to assess the protection and controls compatibility for the equipment in those three sub-systems.

Last, better visibility on CO_2 emission and DC equipment costs is required to assess the economic viability of future DCGs and their financing.

Demonstration project 4 - Management of offshore wind power in extreme high wind situations (STORM MANAGEMENT)

Main findings

- Development of new controller that reduces gradients;
- Gradients for reducing power are less steep with HWRT™ compared to HWSD which leads to a more stable electricity system;
- Using of high wind ride through control reduced the risk of power system instability and blackouts. The maximum forecast error was lowered more than 50%;
- Wind turbine energy output was increased in stormy conditions by using high wind ride through control, which took the cut-off point from wind speeds of 25 meters per second up to 32 meters per second (m/s);
- Gain between 403 and 1,120 MWh of production in the observed storms;
- Nordic hydropower provides flexibility to Western-Denmark against unexpected wind power variations, but this affects the Nordic frequency quality.

Introduction and background

The occurrence of storms raises new challenges when it comes to secure operation of the whole European electricity system with future large scale offshore wind power. With the present control schemes, storms will lead to sudden wind plant shut downs, which in turn is a threat to the whole system security, unless stand-by reserves are ready to take over power demands at very short notice. The challenge that this demo has been addressing is to balance the wind power variability, operating the transmission grid securely during such storm conditions. The more specific objectives of the demo have been to:

- Demonstrate secure power system control during storm passage, using hydro power plants in Norway to balance storm shut down of Horns Rev 2 (HR2) wind farm in Denmark;
- Use existing forecast portfolio available to the TSO to monitor and plan the down-regulation of large scale offshore wind power during storm passages;
- Provide more flexible wind turbine and wind farm control during storms.

Description of project

From a system perspective the effect of losing power due to a storm is no different from other events causing loss of power in the system such as failures of interconnectors or power plants. The challenge for the system is a sudden unexpected change in production and/or consumption. Therefore, from a systems viewpoint, it is important to quantify the magnitude of sudden change of power due to storms. The quality of the forecasts is important for the system in order to anticipate a change in production and therefore take action, for example by activating regulating power or even start up production if necessary.

In future the production mix is expected to change since most countries have plans to integrate large amounts of wind power and a large amount of photovoltaic production. Understanding the important operational processes of today's system is necessary, in order to optimally develop the future transmission system. In Demo 4 six storm events at HR2 were observed and data collected. HR2 is located off the west cost of West Denmark. The wind farm is owned by DONG Energy and the type SWP 2.3-93 turbines are supplied by Siemens. Each wind turbine has a capacity of 2.3MW. With a total of 91 wind turbines, the wind farm has an overall capacity of 209MW.

Within Demo 4 a new controller has been developed where the turbines keep producing at higher wind speeds. When the power is reduced due to high wind speeds this happens gradually. This new controller from Siemens is referred to as High Wind Ride Through™ (HWRT). It will have an impact on the anticipated balance in the system and on the overall system stability, outlined in the sections that follow.

In general wind power production is difficult to predict, especially production from offshore wind turbines that are concentrated in groups over small geographical areas. During stormy weather this reduces the possibility of preventing blackouts that might lead to power system instability. Some of the work in Demo 4 is focused on understanding what happens in the transmission system when production is suddenly lost due to stormy conditions. In order to understand this one has to know how the Western Danish system is balanced.

In Western Denmark detailed schedules for production, consumption and flows on interconnectors are available at all times. Market participants are obliged to send their most updated schedule for a given day to the Danish TSO Energinet.dk at all times, once they get a notification from Elspot, the day-ahead market in the Nordic countries. If trades are made in the Elbas intraday market the participants change their schedules and submit new ones. These notifications have a five minute resolution; they are power-schedules and can be considered snapshots of the power system every five minutes. Offshore wind parks are considered large units and the power producer is obliged to send in detailed schedules. The producer will base these schedules on wind forecasts. For the interconnectors Energinet.dk will generate detailed schedules respecting the ramping rules. Towards Nordic countries and between the Danish areas ramping happens at hour shift +/- 15 minutes at present. Towards Germany ramping happens at hour shift +/- 5 minutes. This means that if there is big change in transit from Nordic countries to Germany this can cause temporarily (~ 5-10 minutes) large imbalances in the Western Danish system.

All the schedules are aggregated and the result is an expected (im-)balance. Based on this expectation, action can be taken, such as the activation of regulating power. By continuously monitoring the expectations for imbalances in the system in the next hour, large imbalances are reduced by activating manual regulating power in due time. Traditionally, reserves are used such that when an imbalance is seen, primary reserves are activated to restore frequency, then automatic (slower) reserves are activated to free the primary reserves and finally manual (slow) reserves are activated to free the secondary reserves so that the system is prepared for the next event. In addition to this way of using the reserves, Energinet.dk also minimizes the realized imbalances by continuously updating schedules and anticipating the imbalances in the system. When activating manual regulating power the bids shall be fully activated within 15 minutes.

From a system perspective the important storm management issue is how much actual production can deviate from a schedule for an offshore wind power plant. Two time frames are important. First the main balancing routine is based on the forecast available 30 minutes before the operational hour. Secondly, the continuous evaluation of the need for adjustment is based on the available forecasts. However, the activation of regulating power has a lead time of 15 minutes. If we can forecast the production 15 minutes or more in advance, then the anticipated reduction of offshore wind can be neutralized by activating regulating power. Due to other restrictions and manual interference it is not possible to activate small amounts of regulating power continuously.

Several events with very high wind speed occurred during the project period - both before installing the HWRT™ controller and after. In total, six events were recorded. Dates for the recorded events are presented in Table 4.1, which also shows which storm controller was installed at HR2 wind farm at that time of the event.

TABLE 4.1 RECORDED HIGH WIND EVENTS

Event nr	Date	Controller
1	11 Nov. 2010	HWSD
2	12 Nov. 2010	HWSD
3	07 Feb. 2011	HWSD
4	24 Sep. 2012	HWRT
5	14 Dec. 2012	HWRT
6	30 Jan. 2013	HWRT

The dynamic controller consists of two systems working in parallel: the first curtails the rotor speed based on the rotor acceleration, while the second curtails the power based on the pitch angle. For the work presented here, the HWRT™ controller was parameterized in the form of power curve, in a manner similar to the High Wind Shut Down (HWSD) control. The wind turbine power curves corresponding to the two control strategies are presented in Figures 4.4 and 4.5, respectively. The wind speed value is defining the behaviour of the wind turbine. The wind speed thresholds for which the wind turbine will shut down, indicated with dotted lines and down pointing arrows in the figures, are based on the instantaneous wind speed (32 and 39 m/s, respectively), the 30 second mean value (28 and 34 m/s) and the 10 minute mean value (25 and 30 m/s).

In both controllers, after a shut-down, the wind turbine will start again when the 10 min mean wind speed will go down to 20 m/s (dotted line with an up arrow in both figures).

Based on both power curves and wind speed measurements from the individual turbines it is possible to simulate output from the wind park. The simulations can then be evaluated for the controller in operation during specific storms. In Figure 4.6 plots are shown for February 7th, 2011, where the storm was observed with the HWSD controller in operation. The detailed data that was collected has been used to simulate the behaviour with the HWRT™ controller. For 30 January 2013 the HWRT™ was in operation and the behaviour of the wind park with the HWSD controller has been simulated.

FIGURE 4.4 HWSD POWER CURVE

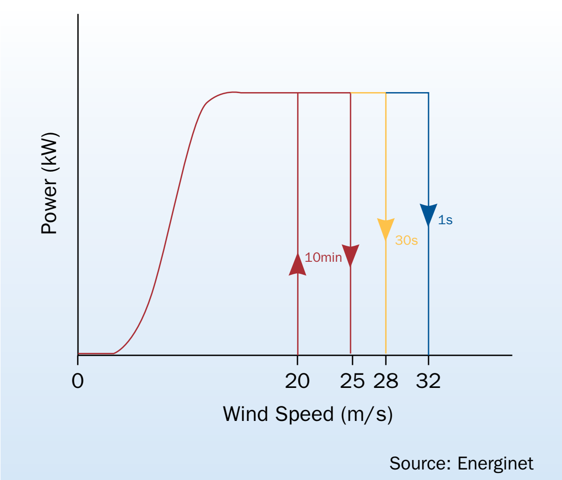


FIGURE 4.5 HWRT POWER CURVE

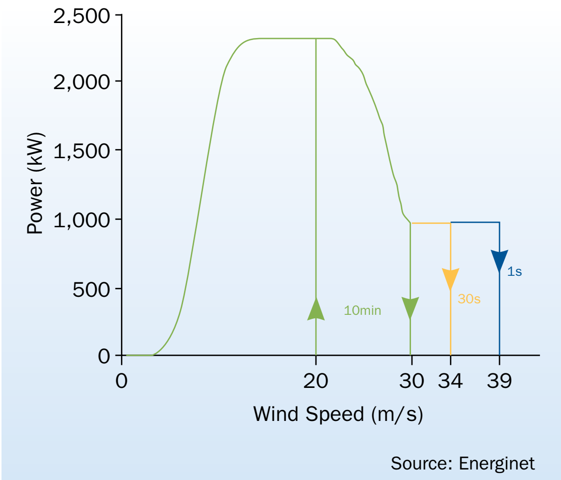
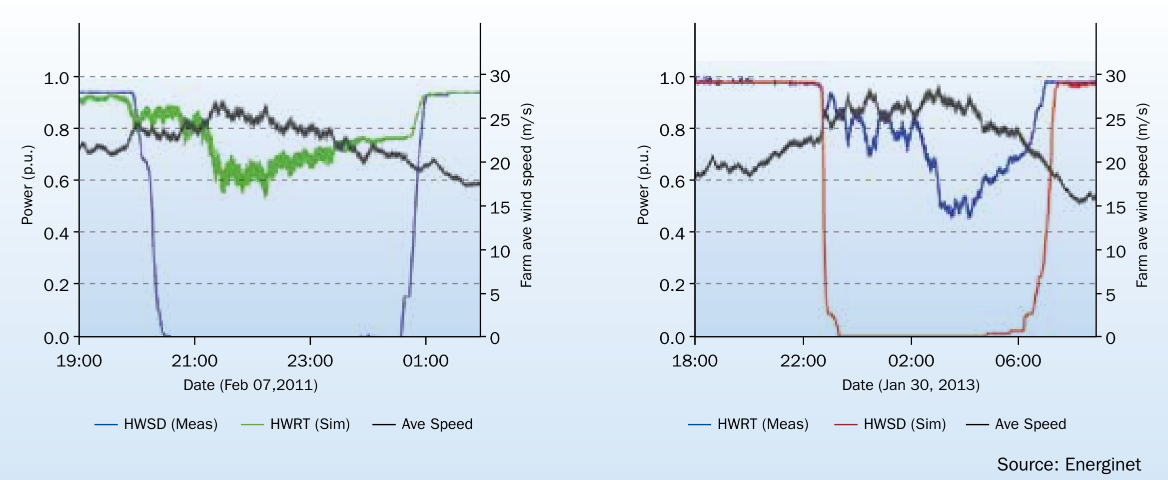


FIGURE 4.6 POWER PRODUCTION AND WIND SPEED DURING THE STORMS ON 7 FEBRUARY 2011 AND 30 JANUARY 2013, RESPECTIVELY



As can be seen from these plots a significant amount of production has been gained and more importantly for the system, the gradient of which production is lost is reduced significantly.

It is not only how the production behaves that causes problems. If the production is forecast precisely enough it might change very fast. Therefore the forecast errors of the storm events have been assessed. The statistics of the forecast errors, for all events, are given in Table 4.2. A high wind event starts when the wind speed reaches 18m/s. The first column gives the maximum forecast error per recorded event, while in the second column the average forecast error is calculated as the average of the maximum error for the events with the same controller – HWSD the first three and HWRT™ the last three. The final column shows the difference between the average maximum forecast errors, or the impact of the HWRT™ controller on the forecast error. The improvement is massive, with the maximum forecast error being lowered by more than 50% - expressed as a fraction of installed capacity. One should take into account that the improvement is solely due to the improved control, since the forecast system in use at Energinet.dk has not been adapted to the new controller, i.e. equivalent HWRT™ power curve. When this happens, the improvement is likely to be even greater.

TABLE 4.2 FORECAST ERROR STATISTICS

<table>
<tr><th>Event</th><th>Max. forecast error (p.u.)</th><th>Average forecast error (p.u.)</th><th>Difference (p.u.)</th></tr>
<tr><td>11 Nov. 2010</td><td>0.80</td><td rowspan="3">0.77</td><td rowspan="6">0.51</td></tr>
<tr><td>12 Nov. 2010</td><td>0.80</td></tr>
<tr><td>07 Feb. 2011</td><td>0.72</td></tr>
<tr><td>24 Sep. 2012</td><td>0.26</td><td rowspan="3">0.26</td></tr>
<tr><td>14 Dec. 2012</td><td>0.18</td></tr>
<tr><td>30 Jan. 2013</td><td>0.35</td></tr>
</table>

TABLE 4.3 ENERGY PRODUCTION DURING THE RECORDED EVENTS

Event	Energy (MWh)		Difference (MWh)
	HWSD	HWRT	
11 Nov. 2010	656	1.194	537
12 Nov. 2010	600	1.003	403
07 Feb. 2011	886	1.556	671
24 Sep. 2012	1.391	2.296	905
14 Dec. 2012	3.480	4.186	506
30 Jan. 2013	1.390	2.510	1.120

In order to assess the difference in the energy produced during the events, the energy production with both controllers was calculated. Table 4.3 shows that between 403 and 1,120 MWh is gained by installing the HWRT™ controller compared to the old HWSD controller. During a year we only expect a few (less than 10) storms. Where the turbines are located it is expected that 1 MW of installed capacity will produce about 4,300 MWh during one year. This means that the HR2 wind farm will produce about 0.9TWh during a year. The result of introducing the HWRT™ controller is increased production during storm events, although the increase in the total annual production is insignificant.

The storm front event on 7-8 February 2011 which was followed by an unexpected failure on HVDC line between Western Denmark and Sweden illustrates the challenges the power system will face in the future when these events occur. In both cases, the measured exchange across HVDC interconnection is compared with the power flow at the border between Western Denmark and Germany. The measured values indicate that a large part of the imbalances caused by storms are compensated by exchanged balancing power, activated from the NOIS list, across Konti-Skan and Skagerrak links. This shows the pivotal role of hydro power in the Nordic system to balance large wind power variations in Western Denmark especially during the storm events. However, the frequency in the Nordic system experienced wide variations due to large deviation on exchange across the Konti-Skan link, as a consequence of the storm. Furthermore, the failure in Konti-Skan link caused an increasing trend in the Nordic frequency: for some minutes frequency goes above the upper threshold for normal operational limits of 50.1 Hz. Comparing the frequency in the Nordic and the Western Danish system shows that the frequency in the Nordic system experienced larger deviations for two reasons:

- Western Denmark is part of the Continental European synchronous system, and Continental European system is much larger than the Nordic synchronous system. Therefore, the Continental system has more inertia than the Nordic system;
- There are delays in the control signals caused by the manual control in the Nordic system, whereas the automatic control system in Western Denmark reacted very fast on frequency deviations. This has improved since the Nordic LFC is running with 100 MW and will improve further when the size increases in the near future.

Results and conclusions

During the project, six high wind speed events were recorded at HR2, with both HWSD and HWRT™ controllers. The analysis has shown that when the wind turbines are equipped with HWRT, the wind power forecast error decreases by more than 50%. Similarly, the energy production during the high wind events increased with the HWRT™ controller compared to the HWSD controller although the amounts are negligible compared to annual production.

The way in which the Nordic system can be used to balance large wind power variations in Western Denmark especially during the storm events, has been analysed. There were wide variations in frequency in the Nordic system due to large deviation on exchange across Skagerrak and Konti-Skan links, as a result of storms and link failures.

The focus has been on explaining the operational procedures that are key to understanding how unexpected events are handled. It is important both to have good forecasts of wind power production so that it can be anticipated as precisely as possible. It is also important to have access to enough automatic restoration reserves to restore balance. The trade-off between these two types of reserves is an on-going discussion.

Work Package 15 - Economic impacts of the demonstration projects, barriers to scaling up and solutions

Main findings

- New offshore network capacity that interconnects national networks allows local surpluses of wind power to be used elsewhere, reserve power to be held, and potentially cheap, zero carbon power to be used instead of more expensive higher-carbon fossil fuel plants;
- It has not been possible to identify a clear preference in 2020 for an H-grid multi-terminal offshore network when compared with radial connections of wind power from offshore hubs to shore plus point-to-point interconnectors;
- The CO_2 reduction benefits arising from a reversal of the merit order of fossil fuelled generation are significant;
- The analysis of offshore wind farms in Denmark shows that thanks to the new High Wind Extended Production (HWEP) controllers like the SIEMENS HWRT™ controller, the largest disturbance due to storms can be reduced significantly compared to the conventional HWSD controller. In particular, maximum ramp rates (in 15 minutes) are reduced from 1,343 MW to 209 MW.

Work Package contribution

Offshore wind power development is still at an early stage. However, it will contribute greatly to future European energy supply. The results of the impact assessment of new HVDC configurations in offshore wind generation suggest that new offshore network capacity to allow increased exchange of power between different countries will be important to realising wind power potential. This new network capacity not only enables local surpluses of wind power to be used elsewhere but also facilitates better reserve power reallocation. However, it might also allow cheap high carbon generation in remote areas to replace lower carbon fossil fuelled plants. Effective pricing of carbon emissions is crucial. Moreover, it has not been possible to identify a clear preference in 2020 for an H-grid multi-terminal offshore network when compared with radial connections of wind power from offshore hubs to shore plus point-to-point interconnectors.

To assess the technical and economic impact of the storm controls, the traditional storm controller High Wind Shut Down (HWSD) has been compared with the High Wind Extended Production (HWEP), which is based on the new storm controller used in Demo 4. A number of high wind speed periods were identified in the data covering the period 2001 – 2011. Each period was simulated with HWSD and HWEP. The results show very clearly that with the HWEP controller the total power dip is significantly lower than with HWSD, and the most remarkable impact is related to the maximum ramping (in 15 minutes) which is reduced from 1,343 MW to 209 MW. Although the frequency stability should be assessed for complete synchronous areas, this indicates that the HWSD control can be a threat to the frequency stability, and that this danger is significantly reduced using the HWEP control. Regarding the impact on balancing during the analysed storm period, the TSO up-regulation expenses for hour-ahead balancing are increased and down-regulation earnings are increased when the HWSD control is replaced by the HWEP control. However, these numbers are negligible compared to the annual net balancing costs.

Work Package 16 - EU-wide assessment of the demonstration projects’ replication potential

Main findings

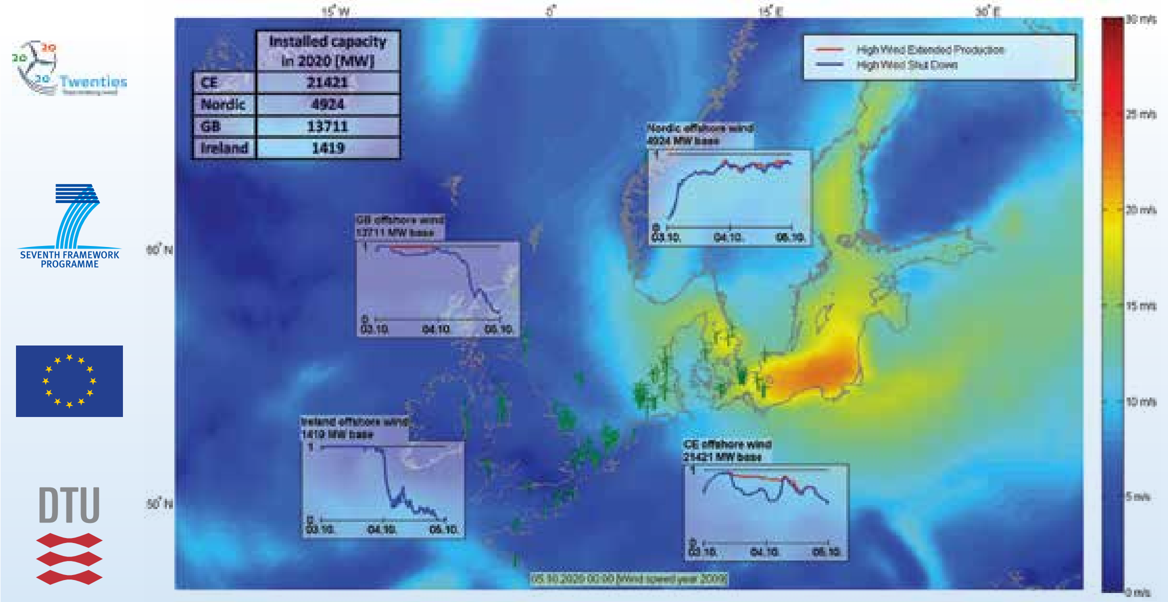
- When offshore grids are used for hydro-wind power balancing, CO_2 prices have a major impact because they can change the merit order, for example of gas and coal fired thermal plants (Demo 3 and Demo 4);
- Wind power forecast errors can be significantly reduced in storm periods, especially on a national level, by high wind ride through controls. At European level, the impact is less significant, but can reduce the volume of frequency containment reserves needed to ensure secure system operation (Demo 4);
- A scenario for a realistic increased hydro capacity in Norway combined with interconnections to UK, Germany and the Netherlands will decrease the total power generation costs by approximately €518 million/year and avoid 10 million tonnes of CO_2 emissions;
- The hydro capacity in Switzerland and Austria can potentially contribute to the integration of the renewable generation in the central western European power system. It could contribute to system stability as a very flexible source of the balancing power and decrease CO_2 emissions. However, having sufficient transmission capacity between Germany, Austria and Switzerland is a key prerequisite.

Work Package contribution

The potential for offshore grids supporting the use of Nordic hydro power to balance wind power generation in North Europe has been assessed in studies supplementing the general studies of HVDC networks in Demo 3 and the balancing of wind power variability in storm conditions in Demo 4. These studies have confirmed that the assumptions of the CO_2 prices can be critical to the findings, because CO_2 prices can change the merit order, for example of gas and coal fired thermal plants.

A survey of the plans for offshore wind power development in northern Europe – including the North and Baltic Seas – has estimated that there could be 40 GW by 2020 and 114 GW by 2030. Simulation of wind power time series with this spatial concentration of large-scale wind power show that the variability of wind power will increase significantly in the European power systems. Figure 4.7 shows an example of how a new High Wind Extended Power (HWEP) such as SIEMENS HWRT™ controller used in Demo 4 will reduce the wind power ramp rates during storms compared to the old HWSD controller which was used offshore until now.

FIGURE 4.7 IMPACT OF NEW HIGH WIND EXTENDED POWER (HWEP) CONTROLLER DURING STORMS



Source: DTU

Based on eight years of meteorological data, the maximum 15 minute ramp rates have been calculated with both storm controllers in each synchronous area as a measure for needed frequency containment reserves. The results show a significant increase in the maximum ramp rates from 2020 to 2030. The effect of the storm controller is visible, but not very significant when looking at the large synchronous areas.

A survey of the potential for increasing hydro power generation and pumped storage capacity in Nordic countries has concluded that the existing 29.6 GW hydro power generation capacity in Norway can potentially be increased by 16.5 GW, and that there is a potential for 10-25 GW of pumped hydro. The most likely scenario is 10 GW increased hydro generation capacity in Norway by 2030.

This work also assesses the value of increased Nordic hydropower production flexibility and the necessary transmission capacity investments in order to reduce the challenges related to wind power production variability in northern Europe.

The scenario with 10 GW increased hydro capacity in Norway combined with interconnections to the UK, Germany and the Netherlands will decrease the total power generation costs by approximately €518 million/year and avoid 10 million tonnes of CO_2 emissions.

A study of how Alpine hydro power can be beneficial for the integration of wind in the central western European (CWE) power system was performed by the TSOs: TenneT TSO BV (Netherlands), TenneT GmbH (Germany), Amprion GmbH, TransnetBW, APG and Swissgrid. Through APG and Swissgrid the Austrian and Swiss hydro power producers were also involved.

A large European market simulation model has been used to perform sensitivity analyses on the quantities concerning grid capacity, alpine hydro capacity and additionally the volumes of wind generation. The influence of these quantities has been analysed on the "economic benefits", CO_2 emission and the reduction of the volume of curtailed wind power. The latter can be seen as a proxy for the integration of wind energy in the electricity system. After the market modeling a grid model had been set up for the studied area of Austria, Switzerland, Germany and The Netherlands. The grid model represents the electrical topology of the transmission grid in 2020 with feed-ins, loads and a simplified lower voltage grid.

Work Package 17 - Reframing licensing and permitting for offshore interconnectors

Main findings

To overcome the barriers and challenges for planning and permitting:

At European level

- Early political commitment to an interconnector project – encourage multilateral cooperation;
- Maritime spatial planning – coordinate planning in the North Sea, for example;
- Apply EU legislation governing harmonisation of planning processes between member states;
- Prepare reference studies on the impact on protected benthos, flora and fauna;
- Clarify the 'heating and cable burial depths' limits - avoid repeating discussion and investigations;
- Settle framework for analysing and evaluating shipping risk studies.

At national and transnational level

- Coordinate between national and trans-boundary planning authorities to facilitate overall evaluation of cable route design;
- Compensation schemes to balance benefits between stakeholders;
- Aim for a one-stop-shop on a (trans-)national level;
- Integral offshore master planning for strategic future projects development;
- Promote use of reference cases (standards, impact assessments);
- Standardise key documents to be used by authorities and stakeholders during the planning and permitting process.

At TSO level

- Public affairs campaign to explain benefits and necessity of interconnectors (security of supply, EU market integration, spread and store strategy, offshore supergrid);
- Improve project management: focus on planning and permitting for the early development of the project;
- Early dialogue with the appropriate regulatory and advisory authorities;
- Focus on onshore part of projects;
- Improve stakeholder management and handling of public opposition.

Introduction and background

The overall aim of WP 17 is to help implement the EU renewable energy policy by proposing ways in which permitting procedures for national and trans-boundary offshore interconnector projects can be made more efficient, more robust and harmonised. WP 17 addresses the issues of smart licensing of offshore interconnectors and focuses on offshore interconnectors with and without a wind farm link-up in the North Sea and Baltic Sea areas. In order to do this, the following objectives were defined:

- Analysing European practices for offshore interconnector permitting, using real life knowledge from recent interconnector projects;
- Identifying barriers to the planning and permitting of interconnectors linking the national transmission system via offshore power cables;
- Drawing up approaches and tools for mitigating these barriers and setting up efficient planning and permitting practices for offshore interconnectors;
- Making recommendations and suggesting best practices for the planning and permitting of offshore interconnectors.

Work Package description

First the challenges and barriers for planning and permitting were identified by investigating 10 recent interconnector projects.

The focus of the second part of the study was to work in detail on the main challenges and possible barriers to offshore interconnector projects identified. Solutions are sought for:

- Permitting and licensing;
- Stakeholder management and public acceptance.

Solutions/recommendations were found through further study and consultation for:

- Technology;
- Business case/project economy;
- System operations.

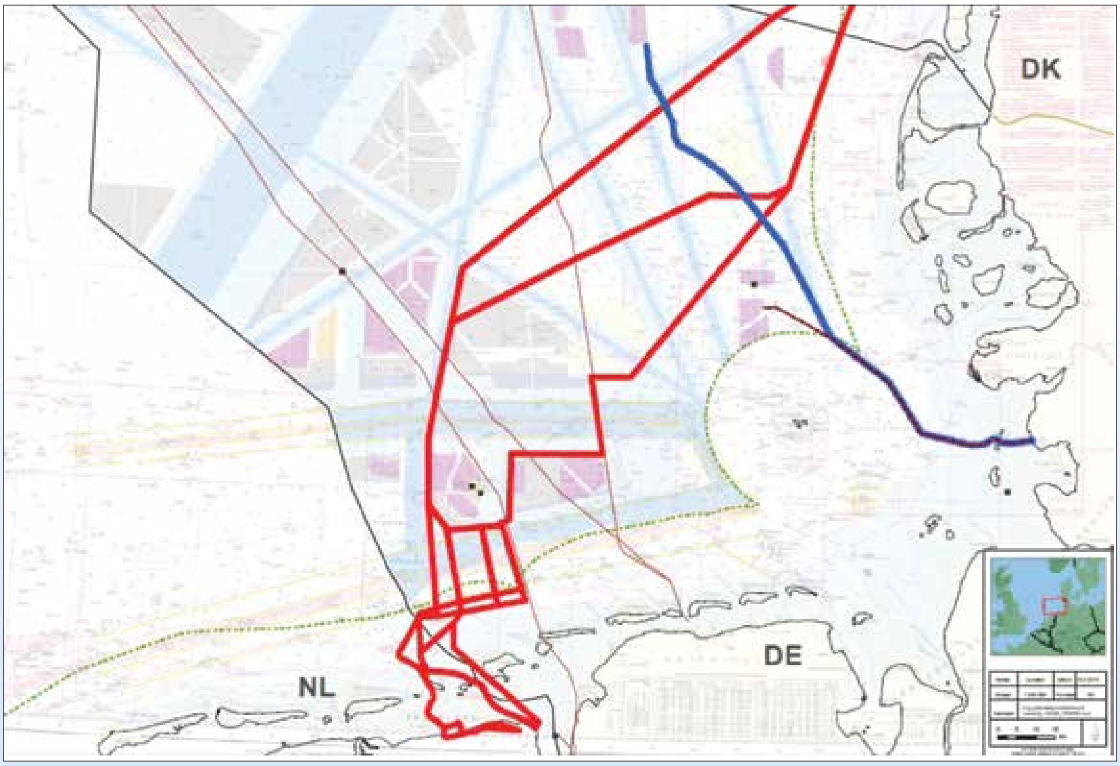
The development of a sound and positive business case can help speed up the permit procedure.

The barriers were analysed by running a virtual case (called TRIFFID after the three leg plant species from the book "Day of the triffids", wrote by John Wyndham in 1951). Lastly, there was a desktop study: "Review of European consenting studies".

A project that requires permits in more than one country faces additional challenges, higher risks of delay and increased costs. The TRIFFID case is an example of a project potentially containing such challenges and risks and is therefore interesting as a case study for the WP 17 project.

The TRIFFID virtual test case represents an interconnector system with multiple landing points (the Netherlands, Germany and Denmark), with a link-up to an offshore wind farm via a multi-station at sea. The case is an example of the complexity of upcoming interconnectors with multiple landing points and with link-ups to offshore wind farms. The case study considers issues concerning ownership, congestion management and capacity allocation, market rules and further technical issues. In order to keep the analysis as specific as possible, the wind farm is assumed to be located in Germany's Exclusive Economic Zone and the trilateral interconnection is assumed to link the bidding zones of the Netherlands (TenneT TSO B.V.), Denmark-West (Energinet.dk) and Germany (TenneT TSO GmbH).

FIGURE 4.8 TRIFFID VIRTUAL CASE



Source: TenneT

The WP 17 synthesis report ("Reframing planning and permitting for offshore interconnectors") presents the work and results of the TWENTIES work package 17 and brings together seven background reports, which serve as research papers for the whole WP 17 study:

I. Report: Optimising licensing and permitting of offshore interconnectors
II. Report: Public affairs and stakeholder management
III. Report: Technical design of TRIFFID configuration
IV. Report: Economy and business case TRIFFID
V. Report: System operations and market design
VI. Report: Review of European studies
VII. Report: Offshore Interconnectors: Challenges and barriers for consenting (D17.1, May 2011)

Results and conclusions

The following recommendations are designed to overcome the planning and permitting barriers for offshore interconnectors:

A stakeholder management guide and a toolbox have been developed, while the analysis has resulted in a number of recommendations for stakeholder management:

- Lobby for national and EU interests in the development of interconnectors;
- Establish a database of research on the most common issues regarding interconnectors;
- Initiate a public affairs campaign to explain the demand for and necessity of offshore interconnectors in combination with offshore grid development (possible themes: national objectives, integration of the North-West European grid, security of supply, maximising the usage of the energy potential, pricing, sustainability, impacts of cable construction);
- Assemble an EU project team to work on projects emphasising EU interests. Specific projects can obtain support from this unit.

TABLE 4.4 CONCLUSIONS AND RECOMMENDATIONS

Conclusions	Recommendations
Environmental Impact Assessment (EIA) procedure is applied by all planning authorities. Lack of transnational standardisation.	A common roadmap for EIA scoping, studies, documentation and practices.
Lot of repetitive work assessing and documenting environmental impacts of cable installation.	Make common compilation and conclusions regarding the impacts of cable installation. A transnational body can serve as the focal point.
Heating and cable burial depths to be reviewed.	Commission an extended scientific study on a European level.
Inefficient cable route evaluation.	Develop instruments to facilitate overall and holistic evaluation of the cable route design.
Balancing the benefits of interconnectors against competing interests.	A dedicated guideline on crossing Natura 2000 areas.
The onshore part is the most critical for planning and permitting of offshore interconnectors.	Increased awareness of the complexity and difficulties of the shore planning and permitting at a very early stage.
No standardisation of frameworks and methods for analysing shipping risks.	Develop common framework and methods.

Results from the technical, economic and operational analysis are:

- Offshore interconnections are very expensive. Using them as a wind park connection affects the flow capacities between countries. From the TRIFFID business case study it is clear that the result is highly dependent on the allocation of the benefits and costs when connecting offshore wind to an interconnector. Many benefits, such as less congestion, will be reaped in countries other than the two main connecting countries;
- Much of the work required in order to make a TRIFFID-like structure operational is challenging. However, since it is part of TSOs' core business and expertise it should be feasible, given sufficient time and resources. For example, the trilateral interconnection requires adapting the existing capacity allocation procedures, IT platforms, as well as associated systems such as scheduling, in order to trade capacity between the Netherlands and Denmark-W.

The review of European consenting studies showed a large degree of consensus on identifying barriers to offshore interconnectors and on how to overcome them. Consensus on how to improve the authorisation and legal framework of offshore interconnector projects underlines the need for new regulatory measures. They should be possible to implement without much opposition in the near future.

TASK FORCE 3 - Improvements in the flexibility of the transmission grid

Demonstration project 5 - Network-enhanced flexibility (NETFLEX)

Main findings

TSOs can plan the network more boldly by monitoring it more accurately and by controlling it more tightly while delivering the same level of reliability:

- The Dynamic Line Rating (DLR) forecaster enables to plan in average 10-15% higher transmission capacities (also called ampacities) thanks to an accurate monitoring of overhead line sag and local wind forecast;
- The Smart Controller enables to coordinate multiple Phase-Shifting Transformers and HVDC links to impact on the flows on some critical branches and to route electricity when it is needed and where capacity is left;
- In order to achieve the same level of reliability, the DLR forecaster can use a more ambitious policy as the Smart Controller enables compensating for over-estimations;
- The Smart Controller also enables to enhance wind penetration thanks to more coordinated actions on multiple Power Flow Controlling devices (PFCs);
- Damping can be reliably forecasted based on flows and injections.

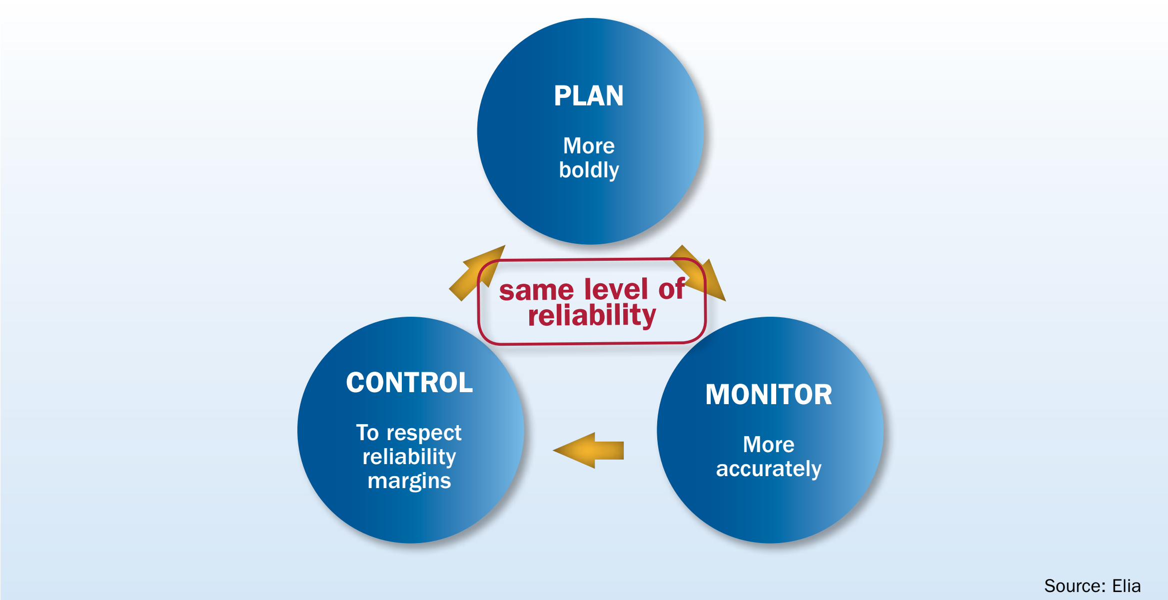
Introduction and background

Power transmission used to be far simpler for system operators to plan and develop. Their geographical focus was narrower and they could rely on their own infrastructure and on adequate lead-times, both when operating their transmission networks and implementing necessary grid extensions. This is no longer the case.

The integration of intrinsically variable wind power has brought unpredictability in the form of sizeable fluctuations in power flows through today's internationally connected transmission networks. It has also further increased the need for grid reinforcement to guarantee security of supply.

However, connecting up and integrating more wind power to accommodate increasingly massive and volatile flows is no easy task. Firstly, it requires tremendous system flexibility. Secondly, upgrading, uprating and installing new overhead lines and underground cables takes time, as does the gaining of permits.

FIGURE 5.1 THE VIRTUOUS CICRLE IN A MORE FLEXIBLE NETWORK



Clearly, more flexible control is needed to cope with variability in a timely and cost-effective manner. The NETFLEX (network flexibility) project set out as part of TWENTIES to devise such a solution and show that enhanced network flexibility can safely deliver greater capacity where and when it is needed and thereby facilitate the integration of wind power.

Solving the wind power variability problem will be crucial for the development of future power transmission networks. We sought to rise to this challenge by combining several emerging technologies to boost network flexibility without compromising operational security. The hypothesis we chose to test was that the enhanced flexibility resulting from this multi-measure approach would enable networks to accommodate larger volumes of wind power and transport it to wherever it was needed, making better use of existing assets.

Our approach was based on the following observations and arguments:

1. Wind cools overhead lines, increasing their transmission capacity, but reliable monitoring by network operators is a precondition for exploiting this extra capacity. Accurate weather forecasts are also invaluable;
2. Some dynamic line rating devices, like Ampacimons, are quick and easy to install and can precisely monitor a network's transmission capacity in real time. The resulting measurements, more accurate than those available in the past, open up the possibility of responsibly exploiting additional capacity without jeopardising safety margins;
3. Potentially, power-flow-controlling devices like phase-shifting transformers (PSTs) and high-voltage direct-current links (HVDCs) can be used to control power flows, alleviate congestion and free up available capacity;
4. Since electricity cannot be stored in large quantities, generated power that is not consumed locally has to be transmitted for use elsewhere. We reasoned that combining more accurate forecasts with smarter controlling would provide a sound basis for bolder planning of flows through existing networks without jeopardising system security. Since diverted power flows can sometimes cause bottlenecks elsewhere, even far away from the original congestion, operational security requirements necessitate an optimal data exchange between TSOs;
5. System stability must also be ensured. This can be done by collecting accurate real-time data from wide-area monitoring systems and phasor measurement units. These data serve as a basis for predicting the stability required to plan flows more boldly;
6. If congestion could be alleviated safely and additional capacity on existing networks freed up, the approach set out above could provide a stop-gap solution until further capacity becomes available and/or until more power generated by variable sources can be integrated into existing networks.

If PFCs could serve to route flows through additional capacities provided by DLRs, we predicted that the benefits of the measures implemented on the basis of these observations would be not merely additive, but cumulative.

In practice, network flexibility could be enhanced by combining two measures designed to increase transmission capacity wherever and whenever necessary:

1. Produce more accurate forecasts of overhead line ratings and system stability;
2. Control power flows more dynamically, further optimising the use of PFCs.

Naturally, any gain in flexibility must not entail any reduction in network stability.

Description of project

Forecasting overhead line ratings more accurately

We applied reliable Ampacimon technology, which uses vibrations to assess the critical sag of overhead lines, to monitor lines' transmission capacity in real time with the utmost accuracy. However, even real-time monitoring is not enough to reap the full benefits of DLRs. To achieve that we had to devise a way of forecasting actual line ratings up to two days ahead. This had never been done before and involved including a number of extraneous factors as well as local weather conditions.

The transmission capacity, or ampacity, of an overhead line is closely related to local weather conditions, especially low wind speeds of 0 to 5 m/s. However, predictions of ampacity based purely on weather forecasts are not accurate enough (see Figure 5.2). So we set out to develop optimally reliable and accurate ampacity forecasts at low wind speeds.

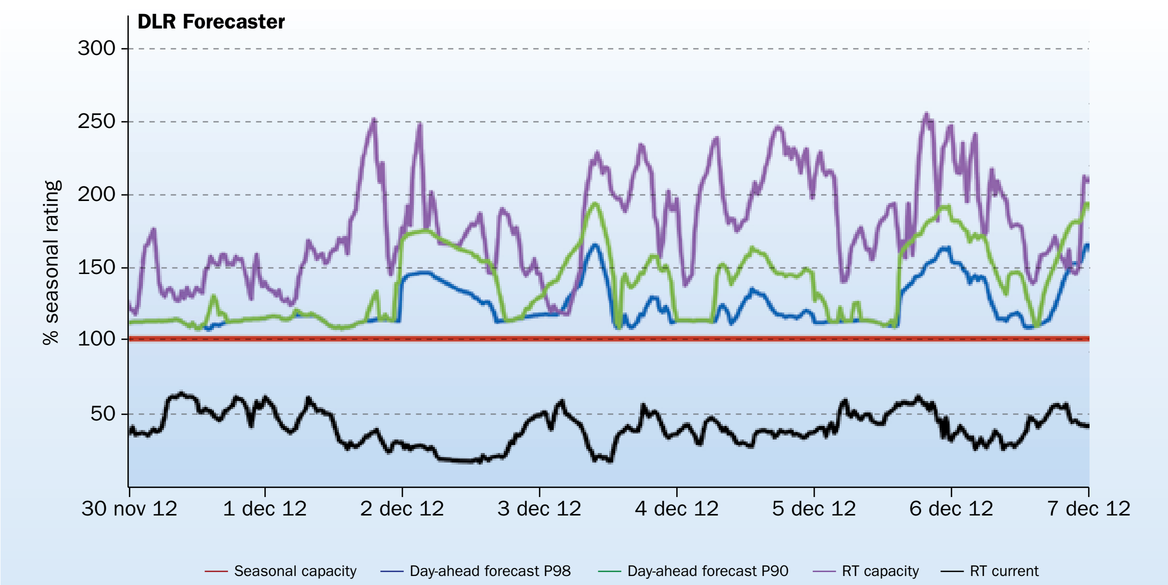
Safety concerns dictate that ampacity must not be overestimated, and since accurate estimates are also important for ensuring security of supply, any forecasts need to be extremely dependable.

Approach

We used statistical models, physics and learning algorithms to develop forecasts based on physical line measurements, predictions of configurable confidence intervals and acceptable, calculated risks and prediction errors.

Integrating field measurements into our forecasting algorithm substantially improved its dependability. Our methodology predicted 2-day-ahead ampacity to 98% confidence (meaning that capacity was overestimated in just 2% of cases) and yielded an average 10-15% gain over static, seasonal ratings.

FIGURE 5.2 COMPARISON OF DAY-AHEAD, REAL-TIME AND WEATHER-BASED AMPACITY FORECASTS OVER ONE WEEK



Source: Elia

Optimising the use of PFCs

Occasionally, flows diverted by power-flow-controlling devices like PSTs and HVDC links, while enhancing network flexibility and alleviating congestion locally, can inadvertently cause bottlenecks elsewhere. Consequently, to avoid unforeseen problems or overspill, whoever controls such diverted flows must remain mindful of the 'bigger picture'. This entails specifying which equipment needs to be monitored when and necessitates closer coordination of the efforts made by the entities or TSOs controlling PFCs over a wide area, such as central western Europe (CWE).

In our view, the best way of achieving this was to develop a smart controller that planned flows internationally, wherever and whenever capacity became available, whilst constantly monitoring stability in the interconnected system.

Some multilateral agreements on PFC coordination already exist, but we deemed them unable to cope with the ever faster pace at which flows will fluctuate in the future. Clearly, such coordination had to be raised to another level.

Approach

We therefore developed an algorithm capable of controlling the tap positions of existing PSTs in the CWE region to resolve congestion problems and possibly maximise N-1 margins on specified lines if required. Separate functions of the algorithm enable it to adapt to a wide range of objectives. For example, it can smooth PFCs' operation by minimising the number of changes throughout a day, which decreases the risk of failure and extends PFCs' useful life.

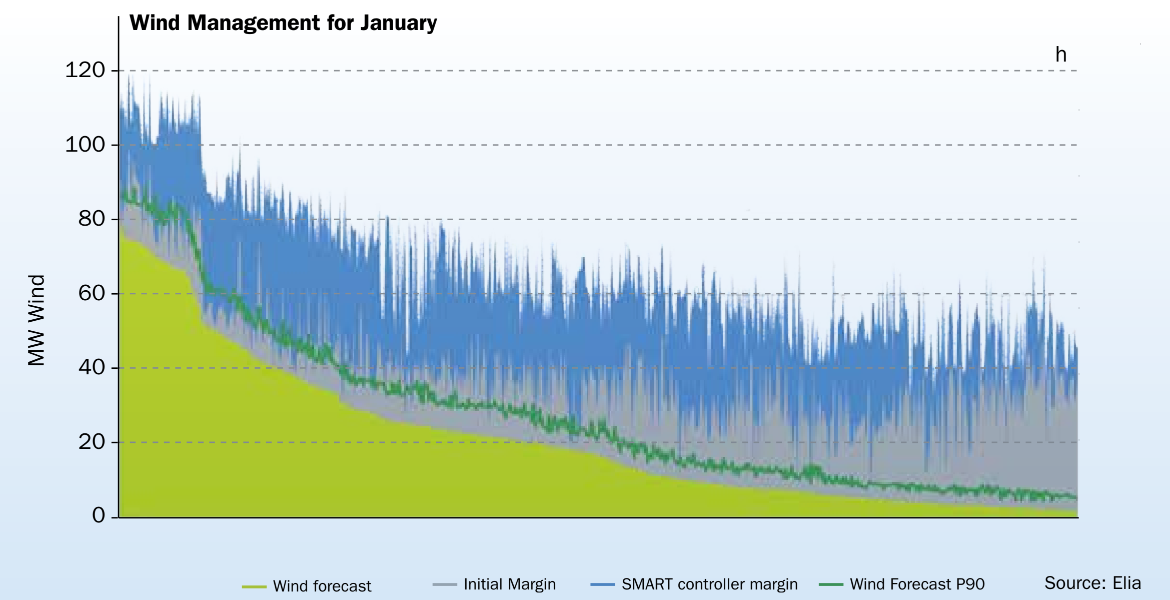
The algorithm's calculations are based on the day-ahead planning dataset, which contains all the necessary network information. To validate the approach, we tested it on extreme actual situations, when a network came close to overload. The algorithm has been fine-tuned by performing parallel runs to monitor results over several weeks.

Enhanced coordination enables TSOs to focus solely on relieving congestion while smoothing operations to avoid frantic adjustments of PFCs. If need be, it can also redistribute flows more evenly throughout the entire network. However, optimising margins on an hourly basis can necessitate occasional major changes in tap positions, creating an operational issue for TSOs to resolve.

Finally, as Figure 5.3 shows, better coordination enables TSOs to manage far greater fluctuations in wind power generation, and hence to find a new way of managing risks when operating the system.

The algorithm's various functions have been intensively tested, tuned and validated by system operators at Coreso.

FIGURE 5.3 COORDINATED CONTROL OF PFCS ENABLES THE INJECTION OF MORE WIND POWER



Forecasting system stability

When there is an increase in bulk flows across a whole synchronous system, its stability can be undermined by poorly damped oscillations. A Wide Area Monitoring System (WAMS) gathering measurements from widely spread phasor measurement units (PMUs) can ascertain real-time system stability by continuously estimating the modal characteristics of such oscillations.

Damping forecasts must be based on actual measurements rather than on prior knowledge because the potential impact of a system's status at any point in time will vary substantially. It is generally accepted that a damping ratio above 3-5% is required to avoid inducing torsional stress in conventional generators or triggering distance protections designed to isolate faulty equipment.

Such knowledge about how controllable assets can affect system stability is essential for producing accurate forecasts.

Approach

We developed an automatic learning algorithm to model the relationship between actual power flows across critical lines in the CWE region and the damping ratio for the system's main modes of oscillation. We noted that using PFCs to increase capacity does not come at the expense of decreased damping.

This approach linked the damping to steady-state network variables estimated on a quarter-hourly basis.

Next, we set out to confirm that forecast flow patterns can indeed reliably predict system stability. The algorithm builds a set of models used to forecast damping ratios, whereby forecast flows (in D-1 and D-2) translate into predicted damping levels per mode.

A key objective was to demonstrate that the risk of error associated with this forecast is sufficiently low to enable planning decisions that will safely diminish system stability margins.

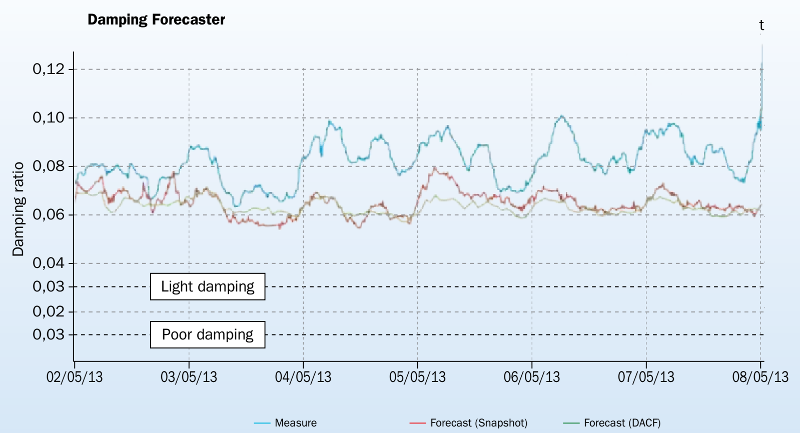
The dependability of our damping forecaster is demonstrated in Figure 5.4. The forecaster was built using a database containing seven months of data (from October to April inclusive). For security purposes, the forecast (snapshot-based in red and DACF-based in green) is conservative compared to the measured damping (in blue). The key observation concerns the striking correlation between forecast and actual damping.

This link between flows and damping means that predicted flows from planned processes can be used to forecast damping levels. The success of this method will hinge on how sensitive it is to errors in forecasting load flows.

TABLE 5.1 CORRELATION COEFFICIENTS BETWEEN FORECAST AND MEASURED DAMPING

Mode frequency	Correlation coefficient
0.15Hz	0.71
0.25Hz	0.67
0.32Hz	N/A
0.50Hz	0.53

FIGURE 5.4 0.25Hz MODE DAMPING FORECAST - DACF-BASED FORECAST IS AS ACCURATE AS THE SNAPSHOT-BASED FORECAST



Source: Elia

Combining the effects

Having confirmed our main three hypotheses, i.e. that:

- Dependable forecasts of overhead line ratings can be made;
- PFCs can be used to greater effect;
- System stability can be accurately forecast.

The only real challenge remaining was to demonstrate that the resulting improvements achieved are indeed greater than the sum of their parts.

Our prime objective was to enhance network flexibility as a way of bridging the period between becoming aware of a congestion problem and building new infrastructure to resolve that bottleneck. To attain this objective we combined the technologies used to validate our hypotheses, intent on increasing transmission capacity wherever and whenever it might be needed.

Approach

To demonstrate how enhanced network flexibility could be achieved, we set out to show that the effects of DLRs and PFCs complement each other in several ways.

Firstly, when the wind is strong enough they are cumulative, enabling greater flows to pass through what had previously been considered as a congested line.

Secondly, when the wind is not blowing strongly enough to cool the line, they complement each other in the event of congestion because PFCs can route some flows through uncongested lines. In other words, PFCs can be used to compensate for overestimations of capacity, enabling the bolder use of this capacity; and flexibility is enhanced because additional cross-border transmission capacities are provided where and when they are needed.

Crucially, this flexibility cannot jeopardise system stability. Therefore, to impose a safety limit on the system's use, we sought to integrate system stability forecasting into our solution.

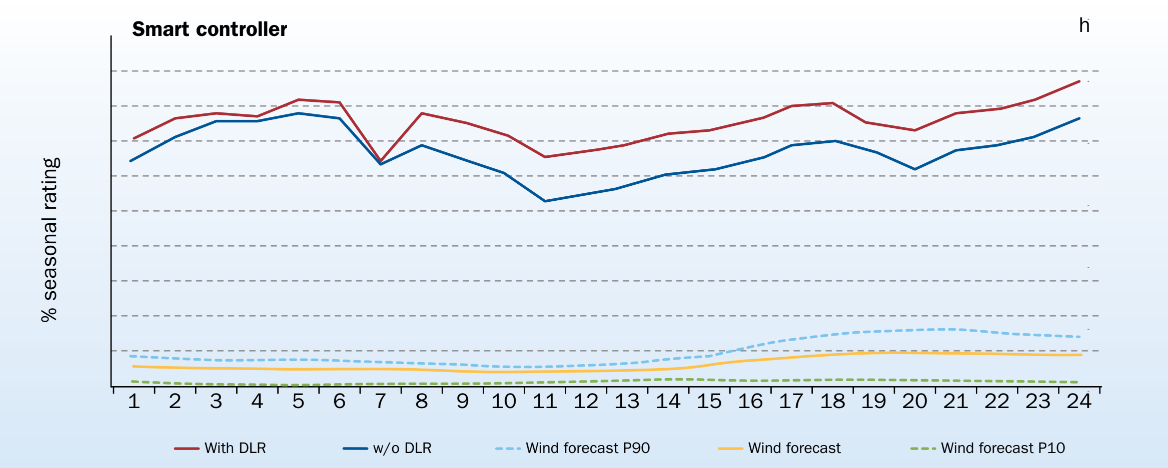
The complementarity of the effects listed above was not easy to demonstrate because DLRs are not ubiquitously deployed. Accordingly, to illustrate the potential efficiency gains we had to extrapolate from a number of case studies performed by Coreso operators. The core tools needed, i.e. algorithm optimisation software and efficient forecasting algorithms, were developed and tested by Coreso over a number of consecutive weeks.

The results suggest that provided the relevant data are available and all the channels of communication involved are efficient and fully functional, our approach is both implementable and manageable.

All that is now needed to optimise day-to-day network flexibility is the large-scale deployment of DLR technologies over a broad area like CWE and for all participating TSOs to gain more experience with smart control, before proceeding with full-scale implementation.

Figure 5.5 below illustrates how DLRs and PFCs can combine to increase transmission capacity wherever and whenever it is needed, thereby lowering the risk of congestion in fluctuating winds.

FIGURE 5.5 MANAGING WIND DEVIATIONS USING DLRS, BETTER COORDINATED PFCS, AND THE TWO COMBINED



Source: Elia

Results and conclusions

Overhead line ratings can be reliably forecast one to two days ahead, significantly increasing the usable transmission capacity of the overhead lines. All that is required is the deployment of DLRs coupled with accurate local weather forecasts.

Coordinating the planning of PFCs enables a more efficient use of the network by shifting flows wherever and whenever capacities are available.

Experiments have shown that even after heeding the security margin required to allow for outages and wind variability, some available capacity can still be used to maximise social welfare, in the short term by increasing cross-border exchange capacities and in the medium term by stepping up and speeding up the integration of renewable energy.

Operating points and, indirectly, wind power generation can either positively or negatively affect the damping of dominant inter-area modes. There is also a relationship between operating points and damping levels. A dependable method for reliably forecasting system stability based on flows and injections has been developed.

Together with a number of central western European TSOs, we demonstrated that the ‘smart PFC’ approach constitutes a sound basis for better coordination of operational planning and that the combination of DLR implementation and PFC control enhances network flexibility and hence increases a system’s ability to cope with wind variability. For now, damping is not a major issue. Even though the role PFCs can play in damping has not yet been fully determined, the predictability of damping has been demonstrated.

Demonstration project 6 - Improving the flexibility of the grid (FLEXGRID)

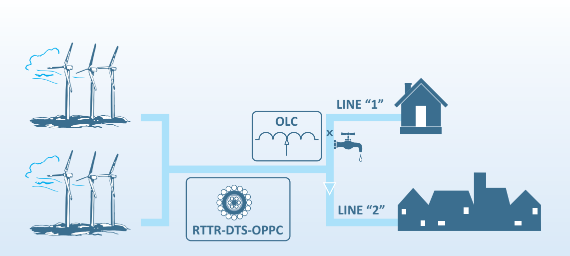
Main findings

- Real-time monitoring of power conductor´s temperature allows up to and over 125% more wind-generated power to be brought onto the transmission grid;
- Excess of energy infeed in specific lines can be redirected to lines with spare capacity in order to use the transmission capacity more efficiently, increasing the controllability and security of the grid and reducing the need for curtailments.

Introduction and background

The integration of renewable energy has had a significant impact on the flow of energy through the power grid, making it necessary to increase network development while maximising the utilisation of the existing facilities. Even when the grid has been adapted to the changes, not all wind power can always be integrated, leading to curtailments. These curtailments sometimes happen when the nominal static ratings (the maximum power that can be transmitted) of the lines are exceeded, making it unsafe to operate the line. However FLEXGRID demonstrated alternatives to help optimise the infrastructure and maximise the integration of renewable generation.

FIGURE 5.6 DEMO 6 CONCEPT-IDEA



Source: REE

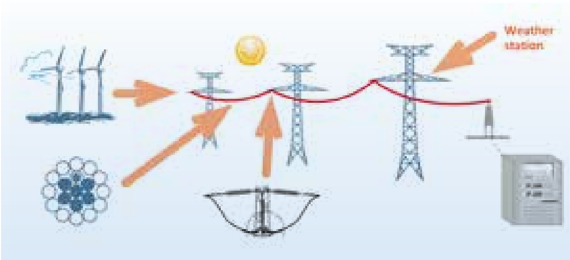
Description of project

Firstly, the power line conditions were monitored in order to assess their maximum capacity in real time based on the real conditions – known as the 'dynamic line rating' – rather than using static seasonal ratings, which are determined by the hypothetical maximum temperature of the conductor. The use of dynamic line rating is closely related to wind power integration because when more wind blows, wind power production increases and the load factor of the evacuation lines is higher. When more wind blows, more transmission capacity is needed, and this is created by the higher cooling effect of the wind over the lines, allowing more power to flow through them.

"Dynamic line rating" implementation and study

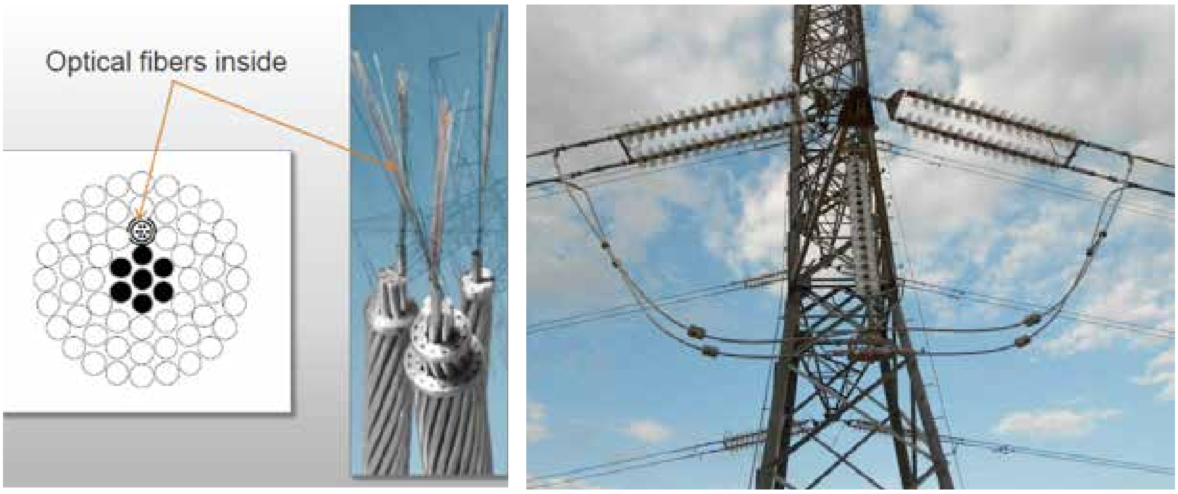
With the technology used in this demonstration project, the temperature along the line is recorded in real time, allowing operators to obtain the transmission capacity rating.

FIGURE 5.7 MAIN COMPONENTS OF OPPC – DTS TECHNOLOGY



Source: REE

A special kind of conductor called an 'Optical Phase Conductor' (OPPC) is used. OPPC is a conventional conductor in which one of the wires has been replaced by a stainless steel tube into which a beam of fibre optics is integrated, in order to measure the thermal behaviour of the conductors over the complete line using a Distributed Temperature Sensor (DTS). Compression mid-span joints cannot be used with these kinds of conductors due to optical fibre splicing. So, in this project the joints were installed in the conductor jumper of several tension towers distributed along the line. The phase selected was the closest to the soil according to facilitate the assembly work.



Detail of OPPC and Straight joint

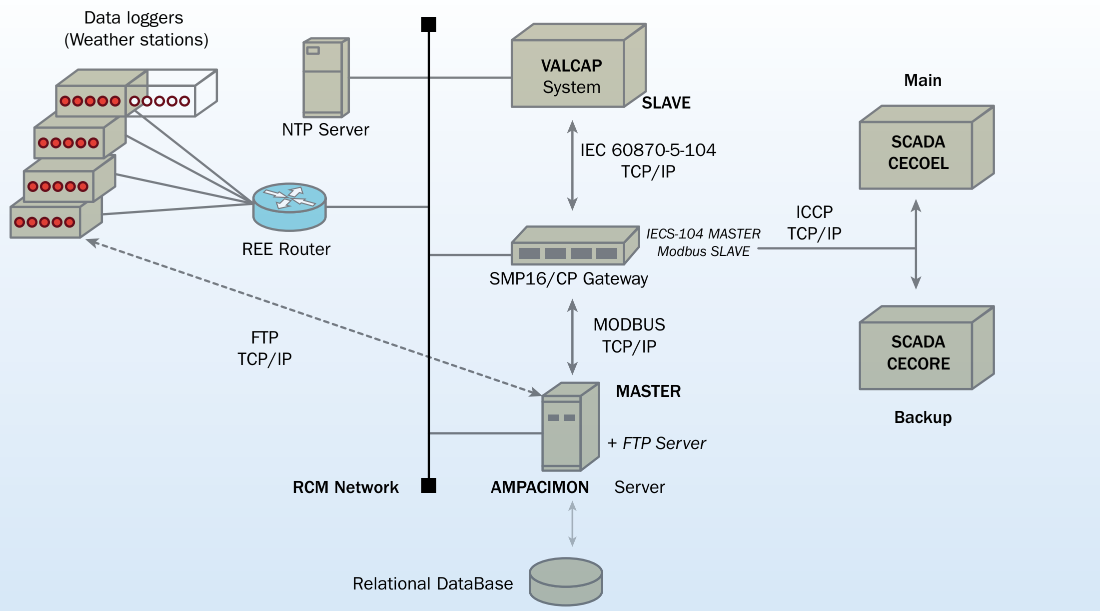
Through a DTS (Distributed Temperature Sensor) system located in the substation, a laser pulse is sent through the fibre optics. By processing this signal it is possible to monitor the temperature with a 2ºC accuracy generating a temperature profile along the entire line (in FLEXGRID demo this profile amounts to 15,000 points, one point every 2 metres over an overhead line 30 km long). The monitoring system (DTS) is hosted in a PC in charge of storing temperature data gathered every 10 minutes and sending it automatically to the other systems involved in the demonstration project.

Weather stations have been installed to record the fast changing weather conditions. In order to increase the accuracy of this weather data, six weather stations were installed in several towers along the route of the line.

All this information is received and stored by the Central System (CSTW system) in Madrid, which requires environmental data in order to carry out ampacity calculations and to develop forecast calculation models.

Detail of termination unit, DTS cabinet and weather station (2)

FIGURE 5.8 COMMUNICATION ARCHITECTURE

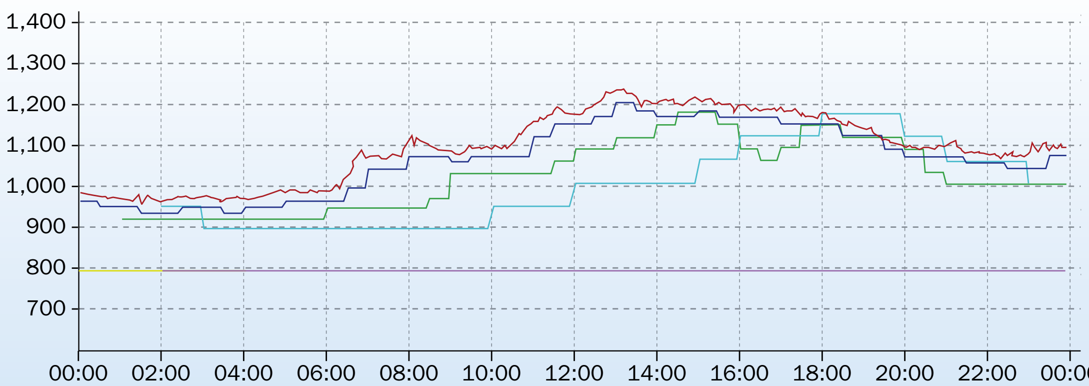


Source: REE

In this development all the necessary information is taken into account: the line current, the temperature information and the weather information of the zone. All this information is managed by the CSTW that is responsible for:

- Storing the information about the line temperature and the weather stations (as backup).
- To carry out the calculations generated by the algorithms to obtain the following values:
  - Computed Section Ampacity: for each section, the algorithm computes the ampacity based on measured weather conditions, conductor´s temperature and current;
  - CTAR Computed Line Ampacity: the algorithm can compute the line ampacity which is the minimum section ampacity based on each section ampacity;
  - CTAO Computed Operational Ampacity: the algorithm is able to compute an operational ampacity which is lower than CTAR but in turn, it will remain valid for 30 minutes ahead;
  - PCTAO Computed forecast: the algorithm computes a forecasted value of CTAO for the next 30 minutes, one hour, two hours and four hours.

FIGURE 5.9 REAL EXAMPLE OF DLR AND FORECAST RATIOS



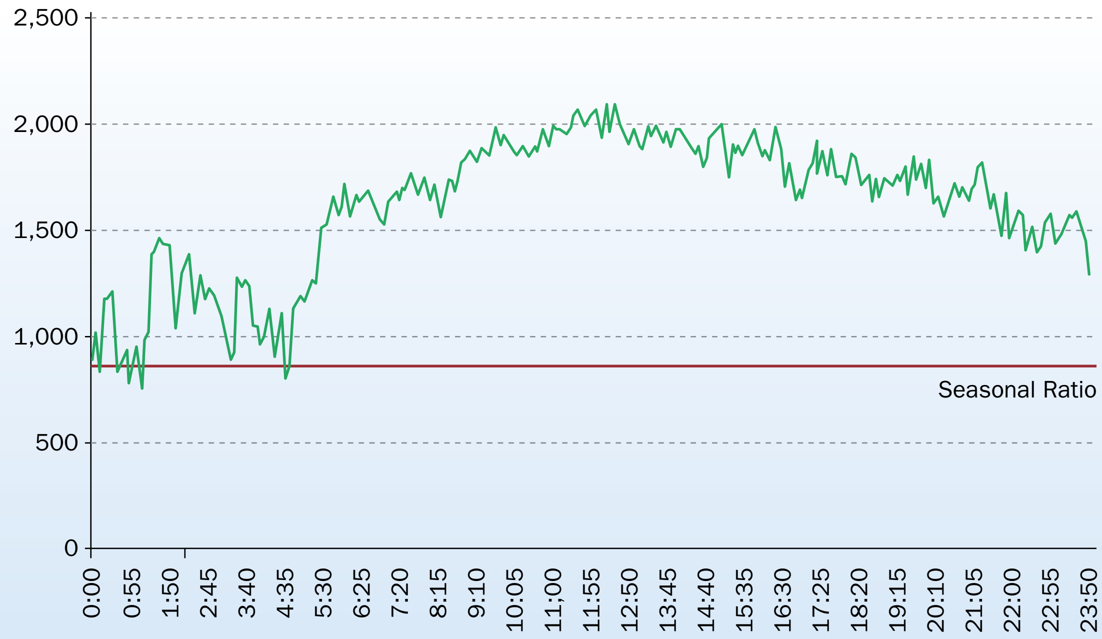
Source: REE

With all this information, several studies are being developed and questions about the behaviour of the line are being answered, such as the following:

- Maximum additional capacity obtained and its variability: on a day with high wind energy generation we could see that we have available up to +150% of additional capacity, 790 MVA Vs 2000 MVA. But, in the same day, we might also observe a capacity below the seasonal ratio with 760 MVA.

As it can be seen, during most of the time (around 95% of the time) the additional available capacity is more than 50% during this day. During this day about 24,000 MVAh of additional energy was integrated, this represents an increase of 125% taking into account the static ratio. Over two weeks, the same information also shows that during 95% of the time, the additional capacity is above 25%.

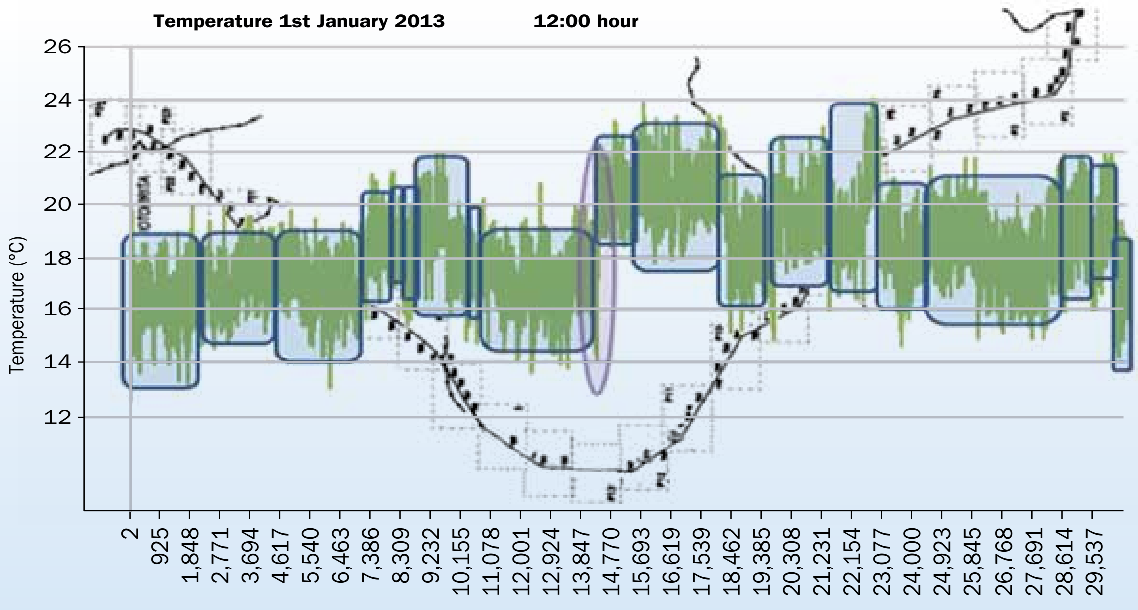
FIGURE 5.10 REAL CAPACITY AVAILABLE 00:00 - 23:55 06/04/2013 (GREATER VARIABILITY)



Source: REE

- Thermal behaviour of the line: the figure on the next page shows the temperature of the line at one specific moment and the orientation of the different sections of the line. The real influence of the combination of the wind direction and section orientation (relative direction of the wind with respect to the section orientation) can be seen on the transmission capacity. That means that the line´s route has a high impact on its future capacity , which implies that the predominant wind direction might become a driver to be taken into account in the engineering phase in the future.
- Location of critical sections: the weakest sections can be readily identified, but, as can be seen, during a single day the weakest part of the line and the part which is a bottleneck can vary widely. Because of this, it is highly valuable to be able to measure the temperature of all of the sections, assuming that a safe operation of the line requires a level of confidence close to 100%.

FIGURE 5.11 DTS TEMPERATURE PROFILE PER OVERHEADLINE SECTION (IN BLUE) VERSUS OVERHEADLINE DIRECTION



Source: REE

FIGURE 5.12 SHARE OF THE TIME THAT EACH SECTION HAS BEEN THE MOST CRITICAL ONE FROM 12/03/2013 AT 21:00 TO 13/03/2013 AT 20:55

Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7	Section 8
5%	19%	30%	5%	2%	7%	10%	4%
Section 9	**Section 10**	**Section 11**	**Section 12**	**Section 13**	**Section 14**	**Section 15**	**Section 16**
6%	2%	2%	0%	0%	0%	0%	1%
Section 17	**Section 18**	**Section 19**	**Section 20**	**Section 21**	**Section 22**	**Section 23**	**Section 24**
0%	1%	1%	0%	0%	1%	1%	0%
Section 25	**Section 26**	**Section 27**	**Section 28**	**Section 29**			
1%	0%	0%	0%	2%			

- Correlation analysis between the power produced by the wind farms and the line Real-Time Thermal Rating. This correlation depends on three factors: the distance between the line and wind farms, the wind speed and its direction.

Secondly, grid operators should be able to dynamically control the power that flows through the line to avoid surpassing the limit by implementing power flow control devices. These devices allow the excess energy to be re-directed from one line to another with spare capacity in order to use the transmission capacity more efficiently, thus increasing the controllability and security of the grid. The use of power flow control devices is closely related to wind power integration because it is an energy source with higher variability requiring an instantaneous power flow control.

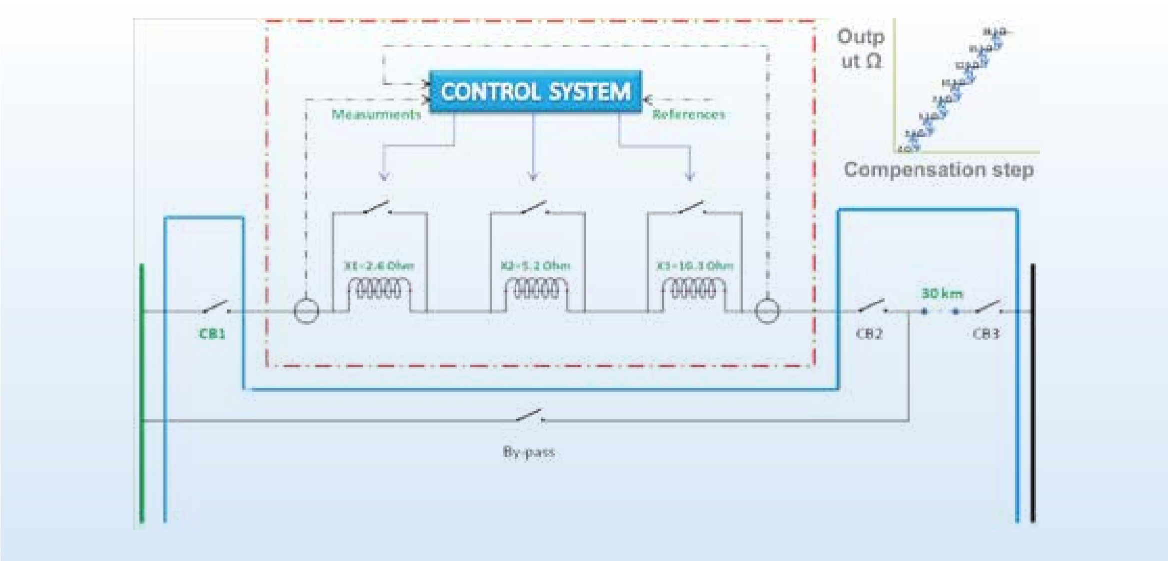
"Overload line controller" implementation and study

The so called 'Overload Line Controller' is characterisd by the integration of traditional power solutions (reactors and switches) and an advanced control system typically implemented in Flexible AC Transmission System (FACTS) solutions based on power electronics.

This solution offers an attractive trade-off in terms of functionality and cost compared to other solutions. It is made up of three reactors of different impedances mechanically arranged in series, driven via individual switches which are parallel to each of the reactors. Through the optimised and controlled action of these reactors, it is possible to achieve staggered limitation of the desired power flow, allowing for the overload of the affected line to be controlled in a steady and a contingency state.

The OLC device has been installed at Magallón 220 kV substation located in series with an existing overhead line, Magallón-Entrerrios rated at 360 MVA. The main nominal features of the device are: 18 ohms (impedance), 1250 A (current) and 85 MVA (three-phase power).

FIGURE 5.13 OLC SINGLE LINE DIAGRAM AND COMPENSATION FEATURES



Source: REE

Taking into account the final design, this device complied with the following objectives:

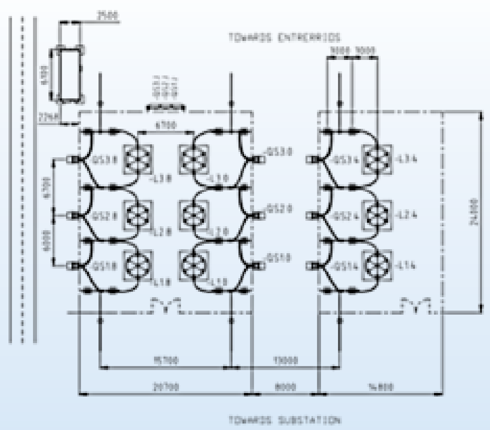
- Modularity: use of standardised air core reactor technology - use of standardised circuit breakers as bypass switches - use of standardised control system (MACH2);
- Portability: containerised control system - bypass switches and reactors possible to relocate;
- Low cost device in comparison with other devices with the same technical capabilities: Information about the device and its installation cost is restricted but further information could be requested to REE and ABB.

One of the most innovative goals obtained is the advanced control that has been adapted to this device, based on automatic calculation of compensation level and of local measurements, permits remote and local control modes as the following ones:

- Power regulation mode (P): the equipment will try to keep the power through the line as close as possible to a defined set point by introducing the required impedance to achieve this target (within its technical limits);
- Power limitation mode (P): the equipment will limit the maximum power flow through the line to a maximum value working only when this limit is exceeded;
- Impedance setting mode (Z): the device will inject a level of impedance according to the selected setting;
- Maximum compensation mode (Z): if a very fast response is needed, this mode acts as the impedance setting mode (Z) but with the maximum compensation automatically. If the operator needs maximum help from the device, this mode could be used by the operator instantaneously, without a setting;
- Emergency control: in case of overload on the transmission line the device will introduce the required impedance to solve it automatically regardless the mode that was activated at that time. This mode is running in parallel with the active one, and can be enabled / disabled locally and remotely.

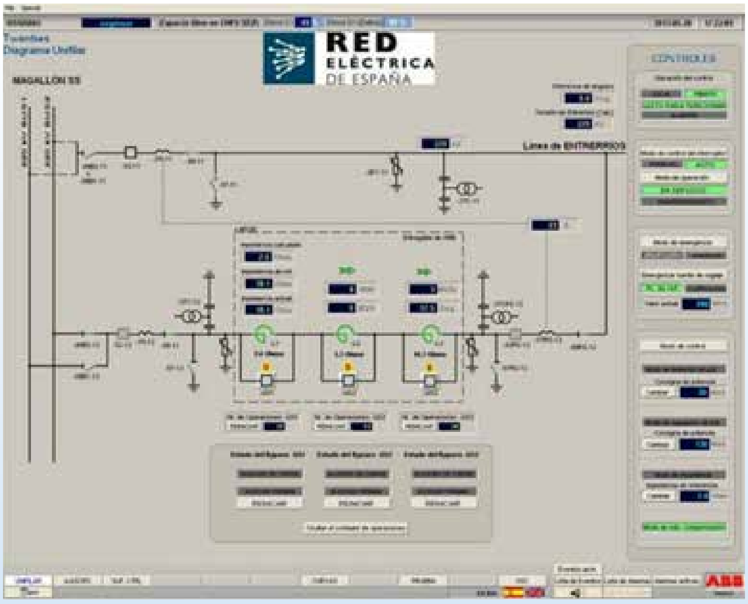
The device uses an advanced algorithm to avoid a large number of switching actions, thus increasing the Overhead Line Controller (OLC) lifespan. Also, the device takes into account possible oscillations in the grid. The power oscillations in the line occur after short-circuit. These oscillations depend on multiple parameters but could achieve a 310% in the line during these short-circuits cleared in 100 milliseconds (ms), or 460% in 250 ms. In general terms the oscillations could be solved between 5 and 10 seconds, and the device has to identify them and act accordingly.

FIGURE 5.14 OLC REAL IMPLEMENTATION AND LAYOUT



Source: REE

FIGURE 5.15 OLC HUMAN-MACHINE INTERFACE



Source: REE

During the commissioning, the device passed the functionality tests satisfactory showing that the control system runs effectively. In addition to these tests, the device is performing different real tests with outstanding results.

Results and conclusions

The results of the demonstration are sound.

Dynamic Line rating

- The maximum transmission capacity is attained in real time . Most days the dynamic ratio throughout the day is more than 10% higher than the seasonal rating. In days with more wind, it could be more than 100% higher over the day. We could assume that using this device the conductor will not be the bottleneck in terms of capacity and the limitation of the electrical substation will have to be taken into account;
- Monitoring along the entire line without having to make estimations or extrapolations. The demo records temperature every 2 metres and every 10 minutes. This provides the operator with complete certainty;
- 'Hot Spots' areas which need maintenance can easily be detected with this technology;
- There is a correlation between wind production and the increase of transmission capacity in lines affected by local weather conditions.

Overload line controller

- Control of power flows in steady state and contingency state. Control strategies based on real-time measurements and set points from dispatching centre;
- Lower acquisition and maintenance cost compared to other power electronics solutions;
- Easily portable to another location if necessary. Easily scalable solution in terms of size and the number of steps.

Both developments have been validated by simulations, lab testing and finally onsite demonstrations. A sensible application of these new technologies would provide extra capacity for the integration of renewable energy, as well as an increase in operational safety. With the same level of safety, these developments will allow the electrical grid to be managed more efficiently by:

- Increasing the availability of infrastructure;
- Optimising the management of the networks;
- Balancing the loads on the lines;
- Setting out immediate corrective actions.

Work Package 15 - Economic impacts of the demonstration projects, barriers to scaling up and solutions

Main findings

- Adequate coordination mechanisms between Dynamic Line Rating (DLR), Power Flow Controlling (PFC) devices and Wide Area Monitoring Systems (WAMS) make the electricity system more flexible within affordable capital and operational costs;
- The analysis performed in the central western Europe (CWE) area shows that PFC and DLR reduce implementation costs and time compared with conventional assets. A smart-controller of PFC in Belgium borders could reduce system costs by €50 million (€250 million if fully deployed in CWE). Broad DLR deployment in CWE would reduce system operational costs by €125 million;
- Analysis of the Spanish system shows that FACTS (Flexible AC Transmission Systems) devices could avoid the redispatch of more than 550 GWh per year, which represents 4.5% of the total energy currently redispatched in Spain. For the tested DLR system, the potential avoided redispatch would be approximately 650 GWh.

Work Package contribution

The most significant economic benefit of FACTS and DLR technologies tested in Demos 5 and 6 is the relief of transmission congestion, which enables more efficient operation of the system. While Demo 5 focused on the increase net transfer capacities provided by the tested devices, Demo 6 focused on local network effects. The economic impact assessment performed for each demo demonstrated that FACTS and DLR devices reduce the need for dispatching out-of-merit generation in both cases, decreasing electricity supply costs. In areas with high wind potential these technologies avoid or reduce wind curtailment, contributing to a more efficient integration of wind generation.

To assess network-enhanced flexibility demo in CORESO, a bottom-up electricity market model that simulates the hourly economic dispatch of generation units and considers cross-border transmission capacity constraints was used to compute system operation costs. In order to assess the economic benefits from the installation of DLR and PFC devices in the CWE region, four cases where DLR and PFC devices are deployed in the CWE region were compared to a business-as-usual case without DLR or PFC implementation. The study showed that the deployment of smart-controller of PFC and DLR devices could reduce system operation costs from 50 M€ (if deployed in Belgium borders) up to 250 M€ (if fully deployed in the CWE region).

The main objective of Demo 6 FLEXGRID in Spain was to measure the benefits of FACTS and DLR devices in the Spanish transmission network in terms of avoided out-of-merit generation costs. A detailed technical analysis using PSS/E (Power System Simulator for Engineering - the tool used by the Spanish TSO for performing power flow analysis) simulated the impact of these devices in four areas of the Spanish transmission grid during real congestion cases when the TSO had to re-dispatch out-of-merit generation. This analysis shows that the installation of the FACTS device in the studied areas could avoid the redispatch of more than 550 GWh per year, which represents 4.5% of the total energy that is currently redispatched in Spain. For the tested DLR system, the potential avoided redispatch would be approximately 650 GWh. The total estimated cost savings from avoiding the re-dispatch of conventional generation are almost €20 million with the installation of FACTS devices and €25 million if DLR systems are used. These values correspond to 3.7% and 4.5% respectively of the total re-dispatch cost in Spain.

Work Package 16 - EU-wide assessment of the demonstration projects' replication potential

Main findings

- Demo 5 showed the decrease of total generation cost by providing additional flexibility at system level thanks to DLRs and a smart controller of PFCs. Local benefits in terms of reduced congestion management costs and improved operation have been assessed by Demo 6. Additional grid flexibility will deliver both;
- The experience gained through Demo 5 and Demo 6 identifies where to install real time thermal rating (RTTRs) or DLRs to capture the cooling benefits from wind and new PFCs for both alleviating local congestion and creating a greater effect at pan-European level.

Work Package contribution

Modelling grid flexibility in long-term simulation tools is very complex as it requires multiple operational strategies to be integrated at once. What is more, a vast majority of today's long-term planning tools use probabilistic approaches to identify bottlenecks and grid reinforcements needed to best serve the market. Modelling grid flexibility requires analyses of sequences of situations to integrate decisions over one day or more. Instead, guidelines have been drafted based on the experience gained through the two demonstrations to plan which technology, among Real Time Thermal Rating (RTTR), Dynamic Line Rating (DLR), Phase Shift Transformers (PST), HVDC links and Optimal Load Control (OLC), should be installed where.

List of Abbreviations

AC	Alternating Current
DC	Direct Current
DCCB	Direct Current Circuit Breaker
DCG	Direct Current Grid
FRT	Fault Ride-Through
HR2	Horns Rev 2 (Danish offshore wind farm)
HVDC	High Voltage Direct Current
HWRT	High Wind Ride Through
HWSD	High Wind Shot Down
LCC	Line Commutated Converter (type of HVDC)
PFC	Power Flow Control
SPS	System Protection Scheme
TSO	Transmission System Operator
VSC	Voltage Source Converter (type of HVDC)

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TWENTIES project

The TWENTIES Project (Transmission system operation with a large penetration of wind and other renewable electricity sources in electricity networks using innovative tools and integrated energy solutions) was coordinated by Red Eléctrica de España, the Spanish Transmission System Operator, and ran from 2010 to 2013. Its aim was to advance the development and deployment of new technologies facilitating the widespread integration of more onshore and offshore wind power into the European electricity system by 2020 and beyond.

TWENTIES is one of the largest renewable energy demonstration projects ever funded by the European Commission under its seventh Framework Programme (FP7), with a total budget of over €56.8 million and an EU contribution of close to €32 million.

TWENTIES was organised around six large-scale demonstration projects grouped into three Task Forces. The demonstration projects were complemented by three work packages focusing on the replicability and scalability of the project results across the EU, and on the non-technological barriers to the development of an offshore grid.