Coordinated control of DFIG-based offshore wind power plant connected to a single VSC-HVDC operated at variable frequency

Mikel de Prada[1], Jordi Pegueroles-Queralt[1], Fernando Bianchi[1] and Oriol Gomis-Bellmunt[1,2]
[1]IREC - [2]CITCEA-UPC

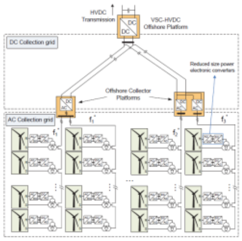
Objectives

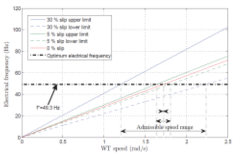
This work proposes an OWPP design based on variable speed wind turbines driven by doubly fed induction generators **(DFIGs) with reduced size power electronic converters connected to a single VSC-HVDC** converter which **operates at variable frequency** within the AC collection grid. OWPP may have several VSC-HVDC converters forming clusters of wind turbines, such that each cluster operates at its own optimal frequency. The aim of this study is to evaluate the **influence of the power converter size and wind speed variability** within the OWPP **on energy yield efficiency**, as well as to **develop a coordinated control** for the **VSC-HVDC converter** and the **individual back-to-back reduced power converters of each DFIG**-based wind turbine in order to **provide control capability** for the OWPP at a **reduced** cost.

Description of the concept

This wind power plant proposal **combines DFIG** wind turbines **with reduced size power converters** (approximately 5-10% instead of 25-35% of the rated power) **and a single VSC-HVDC** converter **which dynamically changes** the collection grid **frequency** (f*) as a function of the wind speeds of each turbine.

- The common **VSC-HVDC provides variable speed control** to the whole wind power plant (or the wind turbine cluster).
- **Reduced size power converters** inside each DFIG wind turbine are in charge of **attenuating** the **mechanical loads** and of partially or totally **compensating** the **wind speed difference among turbines** due to the wake effect.
- **Improved reliability**, increased efficiency due to the **lower losses** and a **cost reduction** are expected to be achieved.
- **Wind energy captured may be reduced** owing to the narrower speed range that can be regulated by a smaller power converter.
- **HVDC transmission** link is **required** to decouple the WPP collection grid from the electrical network.
- **Especially worthwhile for offshore** wind power plants where the wind speed variability among turbines is assumed to be lower than in onshore.





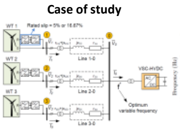
Individual power converters **optimum size** depends on various criteria such as:

- ❑ *Capital costs*
- ❑ *Increased energy capture [1]*
- ❑ *Mechanical load reduction [2-4]*
- ❑ *Fault Ride Through (FRT) capability [5-7]*

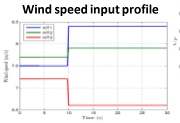
Results

Static analysis

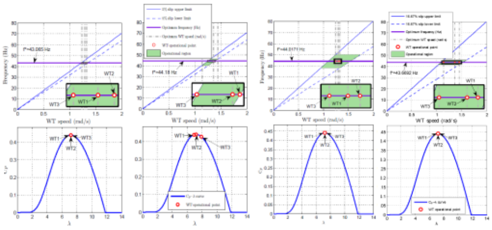
Case of study



Wind speed input profile



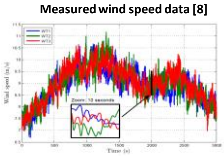
Power converter rated slip = 5% | **Power converter rated slip = 16.67%**



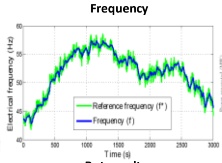
Before 10 seconds | After 10 seconds | Before 10 seconds | After 10 seconds

Dynamic analysis

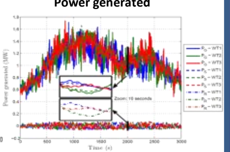
Measured wind speed data [8]



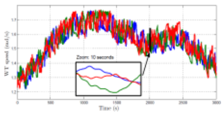
Frequency



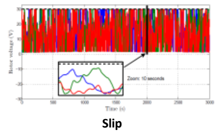
Power generated



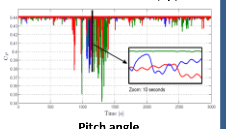
WT speed



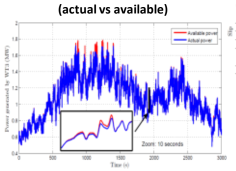
Rotor voltage



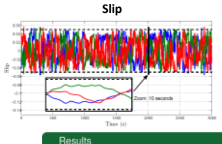
Power coeficient (Cp)



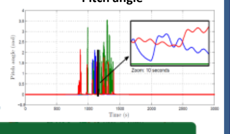
Power generated by WT3 (actual vs available)



Slip



Pitch angle



Results

Rated slip (%)	Energy (MWh) WT1	WT2	WT3	Total energy (MWh)	Energy yield efficiency (%)
5.00	0.9776	1.004	1.0172	2.9988	98.40
16.67	0.9922	1.0104	1.0280	3.0306	99.45
100.00	0.9967	1.0193	1.0315	3.0475	100.00

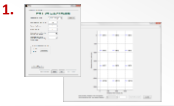
Influence of power converter size and wind speed variability on power generation efficiency

Steps:

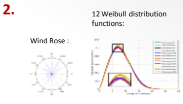
1. WPP layout definition.
2. Wind conditions definition.
3. Wind speeds calculation on each WT by considering wake effects.
4. Application of the optimum electrical frequency search algorithm to maximize OWPP power generation.
5. Computation of energy generated by the OWPP during its lifetime.
6. Calculation of energy capture efficiency as a function of different wind speed variability and power converter sizes.

Case of study
- Number of WTs =12 (3 x 4)
- Power rated = 5MW
- Rotor diameter = 126 m
- WT spacing = 7 D (prevailing) x 6 D (perpendicular)
- Wind conditions:
  - ➢ Wind rose with 12 wind directions sectors.
  - ➢ One weibull distribution function (scale and shape) for each wind direction sector.

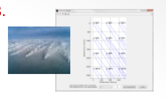
1.



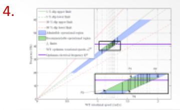
2.



3.



4.

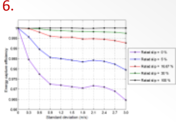


5.

$$P^G = \frac{1}{2}\rho A \sum_{i=1}^{N_{wt}} \sum_{j=0}^{N_{pol}} a_j \left(\frac{2\pi f_e R}{p N_{gr}}\right)^j (1-s_i)^j v_{wi}^{3-j}$$

$$E^G = T \sum_{i=1}^{N_{aws}} \sum_{j=1}^{N_{wd}} P_{ij}^G \, p_{wbij} \, p_{wrj}$$

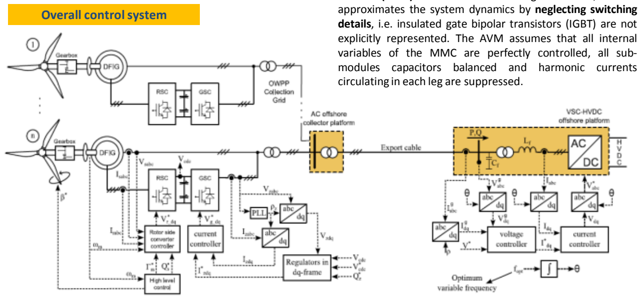
6.



Control design

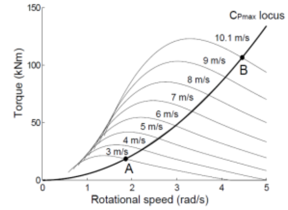
The power converter is modeled using an **average-value model (AVM)** based on switching functions, which approximates the system dynamics by **neglecting switching details**, i.e. insulated gate bipolar transistors (IGBT) are not explicitly represented. The AVM assumes that all internal variables of the MMC are perfectly controlled, all sub-modules capacitors balanced and harmonic currents circulating in each leg are suppressed.

Overall control system

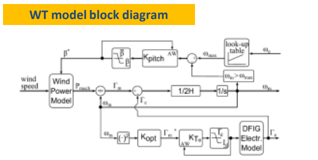


Speed control

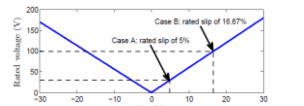
$$K_{C_{P\_opt}} = \frac{1}{2}\left(\frac{c_1 c_2}{c_7}\right) e^{-\frac{c_6 c_7}{c_2} - 1} \rho A \frac{R^3}{\left(\frac{c_2 c_7}{c_2 c_9 c_7 + c_6 c_7 + c_2}\right)^3}$$



WT model block diagram



Rotor voltage saturation



Conclusions

The **performance** of a coordinated control between a DFIG-based OWPP and a single VSC-HVDC converter is **validated** and assessed from both **static** and **dynamic** point of view.
The **results suggest a good performance** of the proposed concept **in terms of energy capture analysis**. Thus, it can be concluded that the size of the power converter installed inside the wind turbine can be potentially reduced. Consequently, **improved reliability**, **increased efficiency** due to the lower losses and a **cost reduction** are expected to be achieved. However, relevant issues such as **fault rid through capability** or **mechanical load reduction** should be also considered to fully assert the minimum admissible power converter size.

References

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Contact: mdeprada@irec.cat