Investigation of DC Converter Nonlinear Interaction with Offshore Wind Power Park System

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Summary

The main objective of the presented study is to evaluate the steady state power system characteristics (correlation between active and reactive power, frequency, voltage magnitude) reflecting influence of the key components such as cables transformers and filters. Modeling of the array (wind park string) cables has been performed using EMT type of simulation software - namely PSS NETOMAC. The grid forming control capabilities of WTG line side converters were also represented in the study. The results obtained from model with finite source reactance are matching well with results calculated by analytical equations. The study further shows that 12-pulse diode rectifier unit (DRU) comparing to 6-pulse DRU concept achieves minimal reactive power consumption at minimal voltage distortion. Harmonic filter could also be significantly smaller in case of 12-pulse DRU, but can't be completely eliminated due to their contribution to the system stability. The 12-pulse DRU fits better to operate with proposed control of WTG converter network bridges. Together they form a robust offshore power system with reduced impact of network impedance on DRU operation.

1 Introduction

One of the main challenges today is to transmit offshore wind power to the mainland grid as efficiently as possible. Efficiency strongly depends on the type of grid access, which becomes more demanding with the wind power plants moving further and further into the open sea. Siemens has developed a new technology (Fig 1.) that enables the efficient transmission of 1.2 Gigawatts of power from farshore wind power plants that are located more than 160 kilometers away from the mainland [1].
The innovative New Grid Access (NGA) approach utilizes offshore AC to high voltage DC (HVDC) conversion by diode rectifiers [2], [3] and a high performance voltage source converter (VSC) located onshore. The diode is the simplest and most robust piece of power electronics the engineer can think of. The diodes are encapsulated together with a transformer and a smoothing reactor in a common tank. This so called "diode rectifier unit"(DRU) looks like an ordinary AC transformer that is installed and maintained like an ordinary AC transformer. The main benefits lie in the reduction of required space; robustness and low maintenance requirements due to the avoidance of air insulated high voltage equipment and simplified cooling.

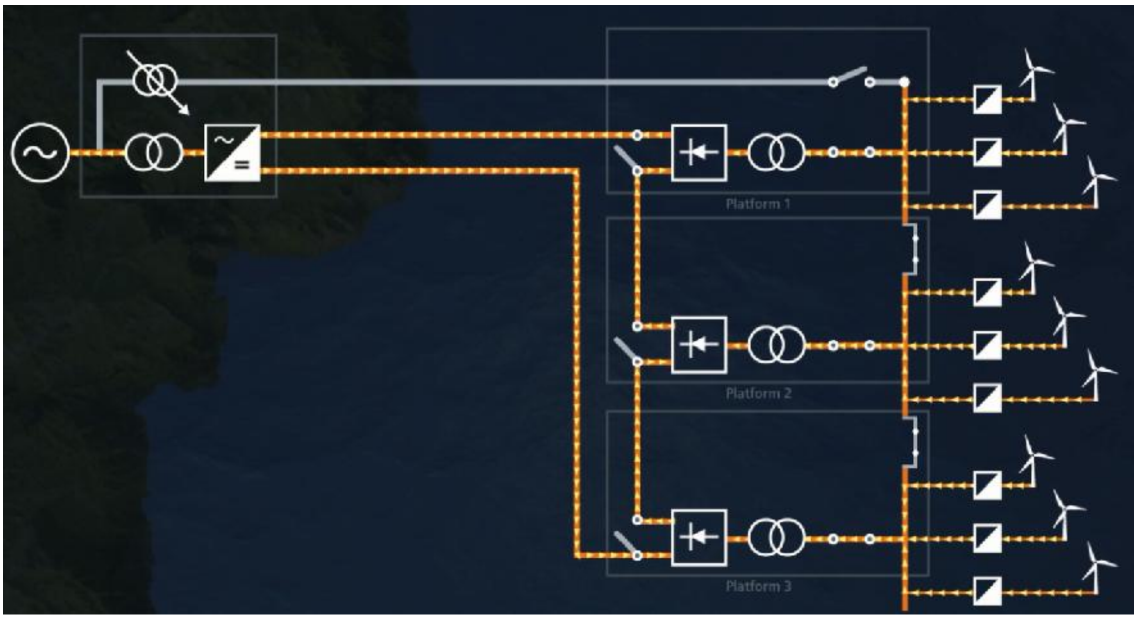

Fig. 1 New Grid Access Solution

	6-pulse DRU	12-pulse DRU
Pro	• Simple transformer (2w) • Allowing higher level of redundancy for serial connected DRUs	• Lower harmonic emissions (THD) • Higher order AC harmonic emissions, Filter is smaller (11/13 and up)
Con	• High AC harmonic emissions (THD) →Large AC filter • Low order AC harmonic emissions (5/7 and up) • Mitigation of higher system distortion requires bigger DC smoothing reactor	• More complex transformer (3w) or more transformers (2x 2w) • Residual harmonics sensitivity

Table 1

Both six and twelve pulse DRU concepts were considered at initial phase of basic design. As first step the pros/cons evaluation shown in Table 1 has been made – however, this did not produce a conclusive answer on the best option on its own. For that reason a voltage and frequency stability assessment of the entire plant – including wind turbine generators (WTG), DRUs and HVDC VSC converter system was carried out using numerical simulation methods. The main objective of the study was to evaluate the steady state power system characteristics (correlation between active and reactive power, frequency, voltage magnitude) reflecting influence of the key components such as cables transformers and filters.

2 Method of evaluation

The analytical theory of ideal commutation process states:

$$\ddot{u} = a\cos\left(\frac{2 \cdot U_d}{U_d + \frac{3}{\pi} \cdot X \cdot f_{op} \cdot I_d} - 1\right), \quad f_{op} = f_1 / f_n \qquad (1)$$

$$Q_{Source} = -\left|P_d\right| \cdot \frac{2 \cdot \ddot{u} - \sin(2 \cdot \ddot{u})}{(1 - \cos(2 \cdot \ddot{u}))} \qquad (2)$$

$$V_{Source} = \frac{\sqrt{2} \cdot U_d}{\frac{3}{\pi} \cdot (1 + \cos(\ddot{u}))} \qquad (3)$$

Equation (1) shows overlap angle ü obtained in case of operation of a diode bridge by an ideal three-phase power system (V_{Source}, f_1). It is depending on DC back voltage U_d, operating point as defined by DC current I_d, commutation reactance X (at nominal frequency f_n) as well as actual power system frequency f_1. The equation (1) visualizes that the commutation process, described by overlap angle $\ddot{u}$, is then completely determined by DC back voltage, DC current, commutation reactance X and power system frequency. Equations (2) and (3) are describing the relation between $\ddot{u}$ vs. reactive power Q_{Source} and power system voltage V_{Source}.

Therefore one degree of freedom is lost from the set of usually four independent steady-state power system quantities $\{V_{Source}, P_{Source}, Q_{Source}, f_1\}$, since for a given frequency f_1:

- $P_{Source}=P_d=U_d \cdot I_d$
- Q_{Source}, V_{Source} see (2) and (3)

According to this point of view Q_{Source} depends on f_1. This fact can be utilized in a droop control concept.
Time-domain simulations are performed to determine dependency of reactive power demand of diode rectifier operation on fundamental frequency f1 as well for six-pulse (B6) as for twelve-pulse bridge topologies (B12).

In the first study case an idealized purely inductive offshore system is investigated Fig. 2-3 and compared with theory regarding reactive power when frequency is varied in a sensible frequency range.

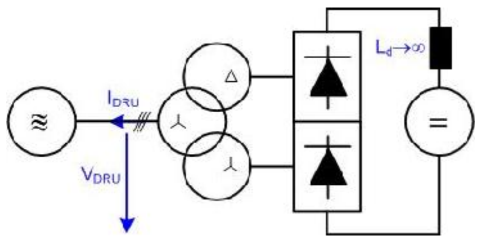

Fig. 2 DRU B6 topology with infinite bus.

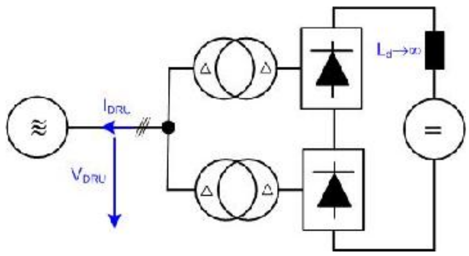

Fig. 3 DRU B12 topology with infinite bus.

In the second step a realistic finite source reactance is considered Fig. 4-5. Again B6- and B12-topologies are compared.
Then the impact of filter circuits and AC cabling on reactive power is studied as well separately as combined under frequency variation. DRU-topologies

under consideration are either six-pulse or twelve-pulse configuration.

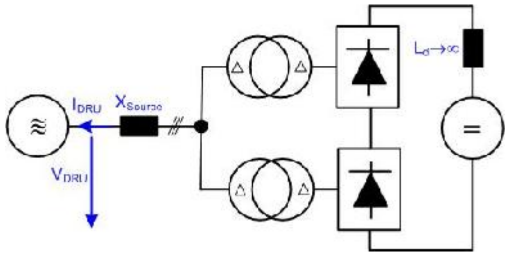

Fig. 4 DRU B6 topology with finite bus

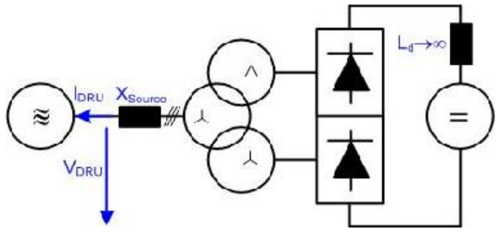

Fig. 5 DRU B12 topology with finite bus.

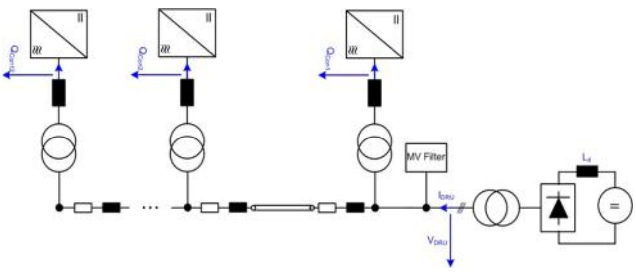

Fig. 6 Representation of OWF cable string – with sections.

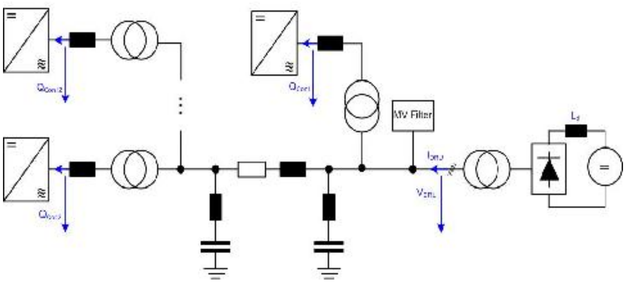

Fig. 7 Simplified representation of OWF string.

Finally, distributed WTG converter feed the considered rectifier bridge whereby the power is collected along one cable string. The used control concept relies on the fundamental frequency in the power system to establish uniform reactive power sharing between individual WTG converters via application of a common droop. An equivalent for the cable string (Fig. 6-7) is determined which requires less computational effort in large system studies.

3 Results

The plots shown in Figs. 8-9 contain curves obtained either from theory in red colour or from time-domain simulations in blue colour for a 204 MW system. Reactive power is smoothed with 10 ms first order filter. Voltage space vector magnitude is shown unsmoothed. Average values are identical when comparing B6 with B12.

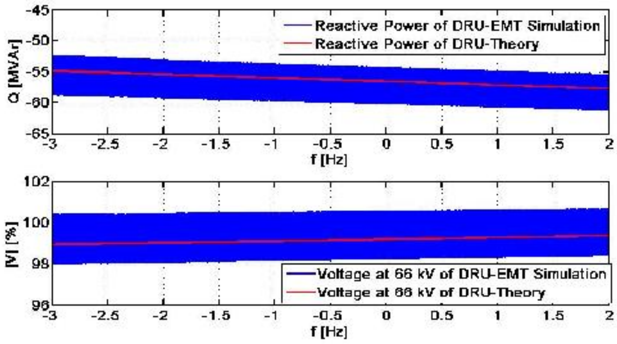

Fig. 8 Reactive power and Voltage at 66 kV – B6.

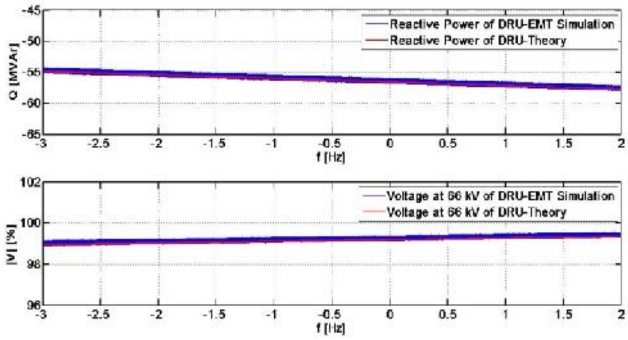

Fig. 9 Reactive power and Voltage at 66 kV – B12.

The analytical theory is now extended to a system with finite source reactance X_{Source} by setting $X := X_{Tr} + X_{Source} \cdot (6/q)$ whereby q=6 for B6 and q=12 for B12. Results are depicted in Figs 10-11.

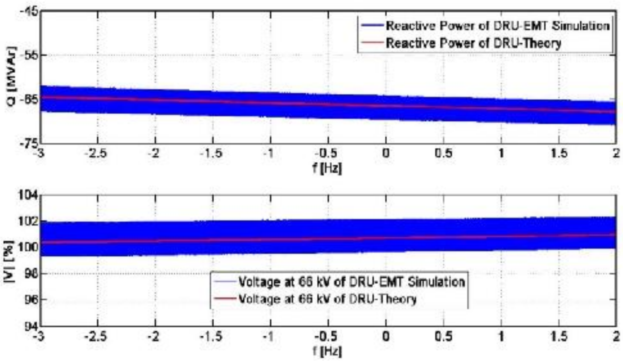

Fig. 10 Reactive power and Voltage at 66 kV – B6 with finite source.

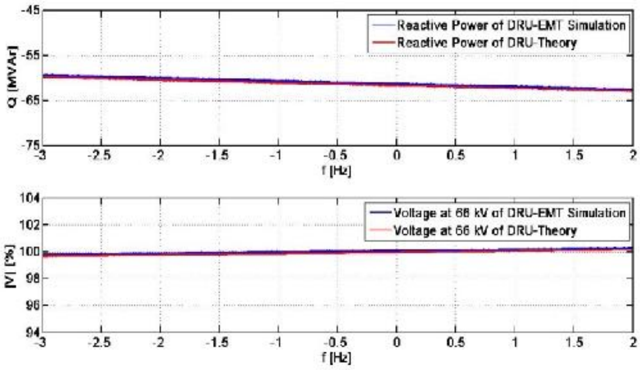

Fig. 11 Reactive power and Voltage at 66 kV – B12 with finite source.

A system of 72 MW is investigated with detailed cable string model. Surprisingly, reactive power demand of B6 is smaller than B12. This occurs due to the high voltage distortion leading to harmonic interaction effects. Cable sections are replicated here with travelling wave model.

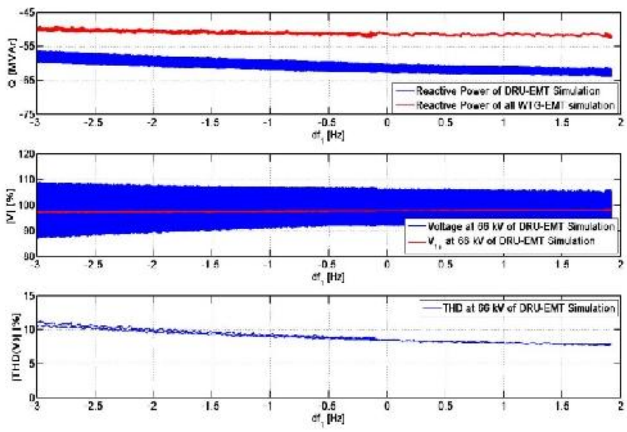

Fig. 12 System with B6 DRUs investigated with detailed cable string model. Depicted Q, V and THD.

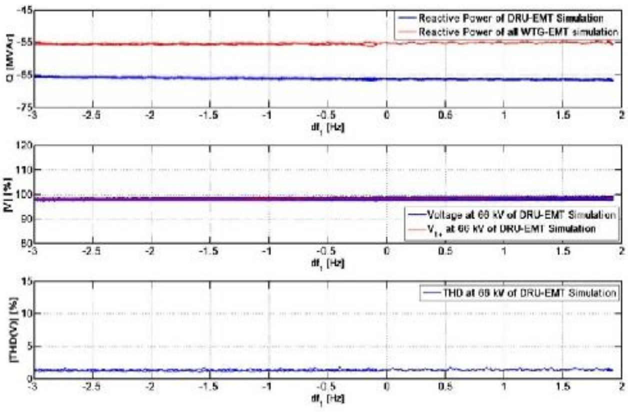

Fig. 13 System with B12 DRUs investigated with detailed cable string model. Depicted Q, V and THD.

4 Conclusions

- *Regarding modeling approach* – It has been found that utilization of simplified infinite bus representation is not sufficient for detailed studies when comparing performance of 6- and 12-pulse diode rectifier units (DRU) concepts. The results obtained from model with finite source reactance are matching well with results calculated by analytical equations.

- *Regarding feasibility* – The 12-pulse concept is more optimal from reactive power consumption perspective. It achieves minimal reactive power consumption at minimal voltage distortion. This will reduce costs for reactive power compensation and cable losses in return for slightly higher costs of 12-pulse DRU equipment in comparison to 6-pulse equipment. Harmonic filter could also be significantly smaller.

- *Regarding compatibility with WTG control* - The 12-pulse DRU fits better to operate with adapted control of WTG converter network bridges. Together they form a robust offshore power system with reduced impact of network impedance on DRU operation.

References

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2. N. M. Kirby, Lie Xu, Martin Luckett and Werner Siepmann, HVDC transmission for large offshore wind farms, Power Engineering Journal, June 2002
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