VSC-HVDC Link to Support Voltage and Frequency Fluctuations for Variable Speed Wind Turbines for Grid Connection

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Abstract-- **This paper presents the use of induction generator turbine machines with simplified frequency control as a direct drive solution for wind energy conversion. An offshore wind farm system is proposed utilising a VSC-HVDC connection. The wind farm will contain variable speed wind turbines driving Squirrel Cage Induction Generators (SCIG). The study will look at the electrical performance of the generators with real wind data and the design control implications with a VSC-HVDC link. The performance of the system is verified by computer simulation using the Dymola/Modelica software platform with the ObjectStab power systems analysis toolbox. This paper presents the design of independently developed optimised power system models for variable speed wind turbine machines with simplified pitch angle and frequency control with a VSC-HVDC link for grid interconnection.**

Index Terms—**VSC-HVDC, SCIG, Frequency Control, Dymola/Modelica.**

I. INTRODUCTION

The application of offshore wind energy is a keystone energy security policy for a number of European countries including Denmark, The Netherlands and the United Kingdom [1]. The renewable energy sector in Ireland has grown strongly in recent years and the Irish government targets 40% of energy to come from renewable sources by 2020, in line with the framework for "20-20-20" EU initiative [2].

Offshore wind locations have the benefit of much higher and more consistent wind speeds than land, which may result in up to 40% annual increased power production according to [3]. Recent developments of offshore wind sites in European waters at substantial distances from the onshore grid have accelerated the demand to look at high voltage DC power transmission (HVDC) as an alternative topology to traditional high voltage AC methods.

HVDC has a number of important attributes including lower environmental impact when utilising underground cables and a higher power capacity for the same voltage/insulation level as AC. Two categories of HVDC transmission topologies exist at present - the Line Commutated Converter (LCC) and Voltage Source Converter (VSC) topology. LCC displays low loss and larger power transmission capacities but with the restrictive drawbacks of low power flow controllability and large filtering footprints. VSC incorporates active and reactive power flow control and also provides support to an independent AC network. Various control configurations for a VSC-HVDC wind farm have been previously reported [4][5].

Variable speed wind turbines offer a number of advantages when compared to their fixed counterparts for wind harvesting applications. Primarily, their ability to comply with connection requirements and the reduction in mechanical loads achieved with variable speed operation have driven their popularity. The squirrel cage induction generator (SCIG) and the doubly fed induction generator (DFIG) concepts are two of the most popular in use today [6][7]. Pitch angle and maximum power tracking control methods can be used to regulate the variability of the incoming wind and restrict the VSC-HVDC link to power fluctuations.

This paper details how power fluctuations of a variable speed SCIG can be controlled using a VSC-HVDC offshore link with pitch angle and frequency control methods. The simplified SCIG construction leads to lower maintenance and is a flexible alternative for renewable applications. This research study also looks to analyse variable wind data for potential offshore locations. Real wind speed data is utilised for the analysis here and the entire system is modelled using Dymola/Modelica software with the ObjectStab power system modelling toolbox [8]. The user can script individual models for each element of a power system, which adds greatly to developing accurate and representative simulations.

The layout of the paper is as follows: Section II will introduce VSC-HVDC operation and control infrastructure for an offshore wind site. Section III will explore the model developed for the turbine with pitch angle control and the generator design equations. Section IV gives an overview of the overall system and the frequency control block developed for the simplified SCIG. Section V presents simulations of the pitch angle and frequency control block and finally Section VI will summarise the paper outcomes and future work direction.

II. VSC-HVDC OPERATION

A. Basic Configuration and Operation

The typical configuration of a VSC-HVDC transmission system is given in Fig.1. The core construction consists of two voltage source converters with IGBT switches, transformers, phase reactors, AC filters, DC link capacitors and DC cables.
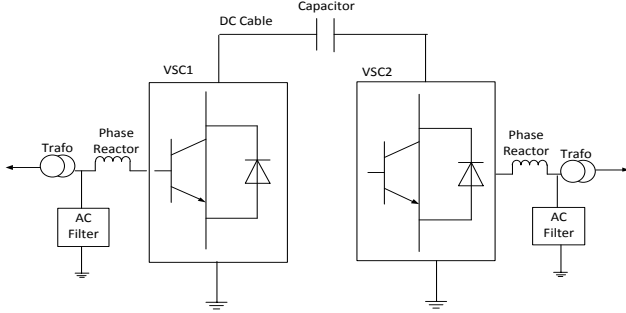

Fig. 1.VSC-HVDC monopole transmission system block diagram

One converter station acts as a rectifier while the other acts as an inverter. This analysis looks at a mono-polar HVDC configuration – the two converters are separated by a single pole line. This configuration is preferred in the case of submarine cable connections for offshore applications [9]. The wind farm side transformer changes the voltage level of the AC network to a voltage level suitable for the converter. The voltage level can be controlled using a tap changer, which will have the effect of maximising the reactive power flow. The phase reactors provide active/reactive power control, power flow between the AC and DC side is defined by the fundamental frequency of the voltage across these reactors [10]. The AC filters are used to eliminate the harmonic content in the output AC voltage, which is created when using PWM (Pulse Width Modulation) techniques. The DC link capacitor is used to provide a low inductance path for the turned off current and it also reduces the ripple on the DC voltage. The DC cables are usually constructed of oil filled and gas pressurised XLPE cable – their main features are low weight and flexibility for transmission [11].

B. Control

The offshore station for a VSC-HVDC system can be considered as a controllable voltage source using PWM techniques to independently control the frequency, the phase angle and the amplitude of the AC voltage according to equation (1) [12]:

$$V_c(t) = \sqrt{2}.Vc.\sin(\omega t + \delta) + harmonics \qquad (1)$$

Where:

$$V_c = m_a . \frac{V_{DC}}{2}$$

m_a : PWM modulation index
ω : Angular frequency of fundamental voltage
δ : Phase angle difference between the AC network and the converter fundamental voltage.

The onshore station is considered as a controllable DC current source. The DC current can be calculated based on the power exchange between the AC and DC sides of the converter, neglecting losses according to equation (2).

$$P_{AC} = P_{DC} = V_{DC}I_{DC} \Rightarrow I_{DC} = \frac{P_{DC}}{V_{DC}} \qquad (2)$$

The control algorithm for a VSC-HVDC system looks to set all the controllable parameters of equation (1) to control the active/reactive power flows independently. The control architecture consists of a fast inner and slower outer loop as shown in Fig.2. The inner control loop controls the current and enables the effective decoupling of the active and reactive power using the two-axis d-q reference frame. The outer controllers may consist of DC voltage control, active/reactive power control and AC voltage control. The reference of the active current can be obtained from the DC voltage controller or the active power controller. The reference value of the reactive current can be derived from the reactive power controller or the AC voltage controller.

For transmitting power from an offshore station to onshore station the reference values of the current controllers are generally configured as [13]:

- The AC voltage control provides the reference values for both active and reactive current at the offshore converter.
- The DC voltage controller provides the reference value for the active current and the reactive power controller at the onshore station.
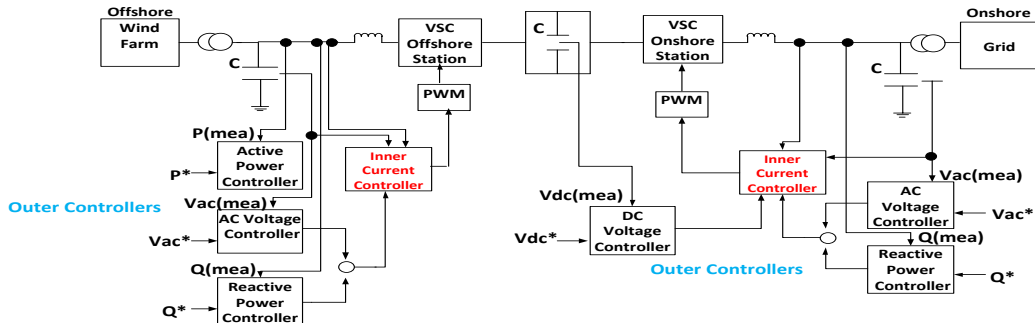

Fig. 2. VSC-HVDC control structure for power transmission, (* denotes reference values).

III. TURBINE AND GENERATOR MODELS

A. Turbine Model with Pitch Angle Control

The mechanical model of the turbine is independent from the generator models. The mechanical power extracted from the wind is a function of the wind speed v_w and the turbine rotor speed w_t and the angular position (pitch angle) of the blades θ_p. The mechanical power P_m is expressed in equation (3) as:

$$P_m = \frac{n_{gen}\rho}{2S_n} C_p(\lambda,\theta_p)A_r v_w^3 \qquad (3)$$

Where:

n_{gen} : Number of machines in the wind farm

ρ : Air density

S_n : Power Rating

C_p : Power coefficient function

λ : Tip speed ratio

A_r : Area swept by the rotor

At low wind speed the pitch angle should be at its optimum value to produce maximum power, while at high wind speeds the pitch angle control should provide an effective means of regulating aerodynamic power and loads produced by the rotor so that design limits are not exceeded. A lookup table script is generated within the simulation to find the optimum reference pitch angle θ_{ref} for wind speeds v_w from 1- 20 m/s for rotor speeds w_t of $0.8 - 1.2$ (pu). This θ_{ref} value is then taken as the pitch angle value for equation (1). Fig.3 displays the interaction between the turbine with pitch angle control and the generator model, which will be examined in the next section.
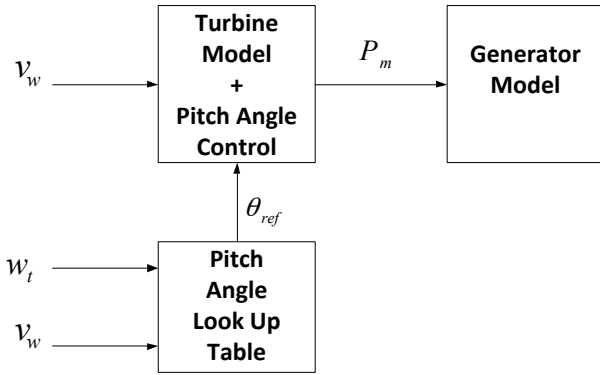

Fig. 3. Turbine model with pitch angle control

B. Generator Model: SCIG

Squirrel cage induction generators provide a robust, reliable and cost effective alternative to DFIGs. SCIGs also display some design drawbacks such as noisy operation and mechanical stresses due to shadow effects. The developed mathematical models for the SCIG model used can be referenced from Milano [14]. A simple illustration of the wind turbine and generator is displayed in Fig.4.
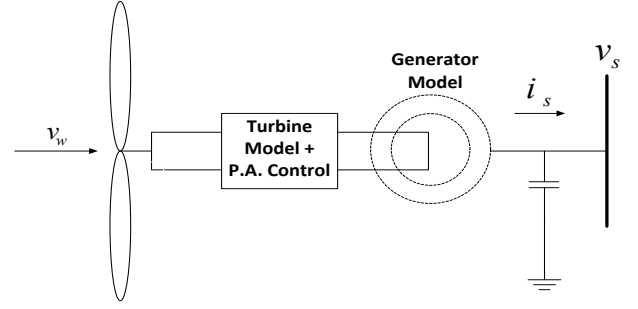

Fig. 4. Turbine Model with P.A. (Pitch Angle) Control and SCIG generator model

The equations for the model are formulated in terms of the d-q imaginary axis, with respect to the network reference angle. In a synchronously rotating reference frame, the link between the network and the stator machine voltages at bus h is given as:

$$\begin{aligned} v_d &= -v_h \sin\theta_h \\ v_q &= v_h \cos\theta_h \end{aligned} \qquad (4)$$

v_h is the network voltage and θ_h is the network reference angle. The active and reactive power produced is expressed as:

$$\begin{aligned} p_h &= v_d i_d + v_q i_q \\ q_h &= v_q i_d - v_d i_q + b_c(v_d^2 + v_q^2) \end{aligned} \qquad (5)$$

Where b_c is the fixed capacitor conductance which is determined at the initialisation step to impose the required network voltage level. The machine electromagnetic differential equations are expressed in terms of the voltage behind the stator resistance r_s and are given as:

$$\begin{aligned} e_d' - v_d &= r_s i_d - x' i_q \\ e_q' - v_q &= r_s i_q + x' i_d \end{aligned} \qquad (6)$$

Where e' is the link stator flux. The link voltages, currents and state variables are described as follows:

$$\begin{aligned} e_d^{'} &= \Omega_b(1-\omega_m)e_q' - (e_d' - (x_0 - x')i_q / T_0' \\ e_q^{'} &= \Omega_b(1-\omega_m)e_d' + (e_q' + (x_0 - x')i_d / T_0' \end{aligned} \qquad (7)$$

where Ω_b is the system rated frequency, ω_m is the rotor angular speed. x_0, x' and T_0' are obtained by :

$$x_0 = x_s + x_\mu$$

$$x' = x_s + \frac{x_r x_\mu}{x_r + x_\mu} \qquad (8)$$

$$T_0' = \frac{x_r + x_\mu}{\Omega_b r_r}$$

where r_r is the rotor resistance, x_r is the rotor reactance, x_s the stator reactance and x_μ the magnetizing reactance.

Finally, the electrical torque τ_e is defined as:

$$\tau_e = e'_d i_d + e'_q i_q \qquad (9)$$

Section IV of the paper will now look to combine the turbine/generator model with a VSC-HVDC link.

IV. TURBINE-GENERATOR-HVDC LINK MODEL

The turbine/generator model with a VSC-HVDC link is presented in Fig.5. The Dymola/Modelica model for the VSC-HVDC link was developed by ABB Corporate Research and the major design parameters for the overall system are presented in Section V.
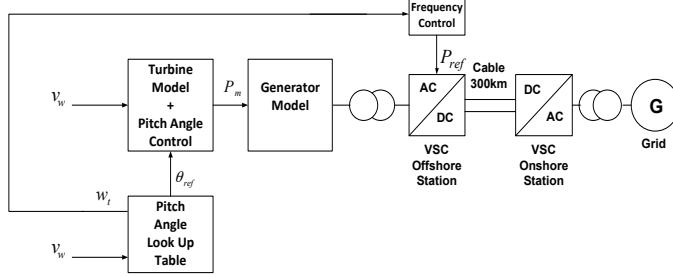
Fig. 5. Wind Turbine Model with Pitch Angle/Frequency Control utilising a VSC-HVDC link.

For the simulation VSC-HVDC control is configured as follows:

- The offshore station controls the active power and AC voltage.
- The onshore station controls the DC voltage and the reactive power.

For the SCIGs with a VSC-HVDC transmission link developed here, a frequency control loop is included to stabilise the frequency for wind fluctuations. A frequency control block is included in the offshore VSC-HVDC station. Fig. 6 gives the layout of the frequency controller for the offshore station and Table I gives the tuned control parameters used in the simulation to stabilise AC voltage.
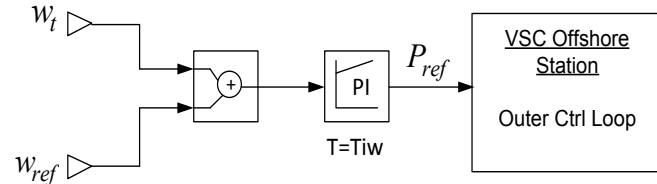
Fig. 6. Frequency control block

TABLE I
FREQUENCY CONTROL PARAMETERS

Parameter	Name	Value
Kpw	Frequency Control Prop Gain	100
Tiw	Frequency Control Time Constant	1
w_{ref}	Frequency Reference	1

V. SIMULATION

In order to verify the effectiveness of the proposed system a number of simulations have been performed. The major system parameters are presented in Table II.

TABLE II
PARAMETERS FOR THE SYSTEM SIMULATION

Parameter	Value
Number of Machines in Wind Farm	4
DC Cable Length	300 km
VSC Max Pole to GND DC Voltage	320 kV
VSC Max Power DC	547 MW

Fig.7 displays the effectiveness of the pitch angle controller for the turbine/generator model from Section III. The pitch angle control tracks the wind speed closely while with no pitch angle control the output power fluctuates greatly which could result in damage to the VSC-HVDC converter.
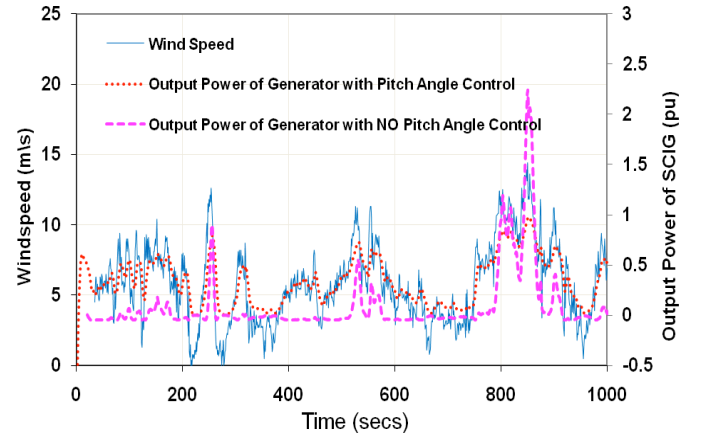
Fig. 7. Pitch angle control performance with variable wind speed data

The performance of the offshore controller with frequency control block from Section IV is depicted in Fig. 8. The controller is positioned at the offshore VSC station and is tuned with the parameters from Table I to give a stabilised AC voltage with respect to the reference over a selected time period.
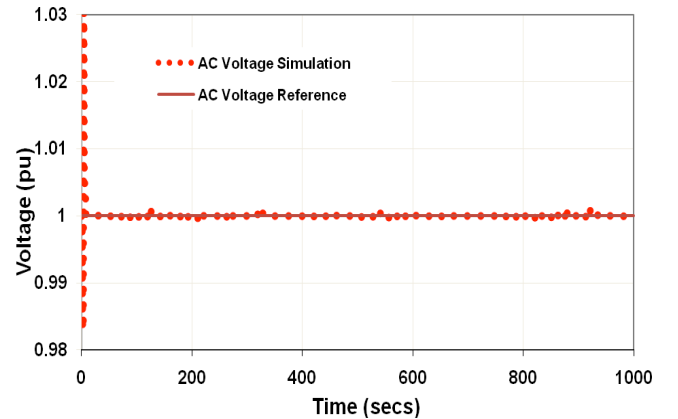
Fig. 8. AC voltage control at offshore station

VI. Summary

This paper has introduced the application of variable speed wind turbines with simplified control methods to regulate pitch angle and frequency/voltage fluctuations with a VSC-HVDC link for an offshore wind farm. A number of interesting research themes have been investigated in the paper including:

- Development of programmable independent models for power system simulation with Dymola/Modelica.
- Pitch angle and frequency control integration to interface the SCIG with VSC-HVDC link for power transmission.
- Simulation of the proposed system with a detailed industry standard VSC-HVDC Model.

Future studies will look to develop the work presented here and investigate a control infrastructure for possible grid integration.

VII. Acknowledgment

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IX. Biographies

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