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Variable Frequency Operation of an Offshore Wind Power Plant with HVDC-VSC

V. Gevorgian, *Member, IEEE,* M. Singh, *Member, IEEE,* and E. Muljadi, *Fellow, IEEE*

***Abstract*—Based on DOE study, wind power generation may reach 330 GW by 2030 at the level of penetration of 20% of the total energy production. From this amount of wind power, 54 GW of wind power will be generated at offshore wind power plants. The deployment of offshore wind power plants requires power transmission from the plant to the load center inland. Since this power transmission requires submarine cable, there is a need to use High-Voltage Direct Current (HVDC) transmission. Otherwise, if the power is transmitted via alternating current, the reactive power generated by the cable capacitance may cause an excessive over voltage in the middle of the transmission distance which requires unnecessary oversized cable voltage breakdown capability.**

The use of HVDC is usually required for transmission distance longer than 50 kilometers of submarine cables to be economical. The use of HVDC brings another advantage; it is capable of operating at variable frequency. The inland substation will be operated to 60 Hz synched with the grid, the offshore substation can be operated at variable frequency, thus allowing the wind power plant to be operated at constant Volt/Hz.

In this paper, a constant Volt/Hz operation applied to the Type 1 wind turbine generator. Various control aspects of Type 1 generators at the plant level and at the turbine level will be investigated.

***Index Terms*—wind turbine generator, offshore wind power plant, variable speed, induction generator, HVDC, HVAC, and renewable energy.**

I. INTRODUCTION

BASED on the "20% Wind Energy by 2030" DOE study, wind power generation could reach 330 GW by 2030 at the level of penetration of 20% of the total energy production. From this amount of wind power, 54 GW of wind power will be generated at offshore wind power plants [1]. The deployment of offshore wind power plants requires power transmission from the plant to the load centers inland. According to [2], the U.S. gross offshore wind resource prevails for the areas of transitional depths (30-60 m) or deepwater areas (>60 m) that are generally located at farther distances from the shore.

The offshore wind power plants (WPPs) can be connected to the grid using either AC or DC transmission. The use of high-voltage direct-current (HVDC) is justified for submarine transmission distances longer than 50-60 kilometers [3]. The use of HVDC brings many advantages that are well described in technical literature. One advantage that may be of additional benefit to offshore wind power is its capability to operate at variable frequency. While the onshore converter substation will be operated at 60 Hz synchronized with the grid, the offshore converter station can be operated at variable frequency.

In this paper, a constant Volt/Hz operation of offshore voltage source converter (VSC) based HVDC terminal applied to the offshore WPP that consists of Type 1 (squirrel-cage induction generator/SCIG) wind turbine generators. Similar single or multi-terminal offshore system topologies were previously analyzed in [4], [5], and [6] with the focus on dynamic and transient simulations for various events, including changes in wind speeds and voltage faults [8], [9]. Here we focus on steady-state performance of constant Volt/Hz operation of Type 1 offshore- based WPP.

A general layout diagram of VSC-HVDC interconnected offshore WPP is shown in Figure 1. In the case of Type 1 wind turbine generators (WTG), under steady-state conditions all units operate at constant rotational speeds that depend on a frequency set by VSC and wind speeds at each individual WTG. The variable frequency operation that is well known to improve energy capture on a single turbine level can also be applied on a group level. It is important to keep in mind that conventional induction generators and transformers are designed to operate most efficiently at a constant Volt/Hz ratio. This means that voltage of the collector system must change with the frequency to maintain this ratio constant. Below, we investigate issues of variable frequency, - constant Volt/Hz steady-state operation of Type 1 WTG-based WPPs with VSC-HVDC terminal, and estimate gains in energy capture associated with such operation.

In this paper, the following sequence will be followed. In section II, we discuss constant Volt/Hz operation of VSC-HVDC interconnected WPP. In section III, the operation of a single Type 1 WTG is described. In section IV, the effects of aggregation and wind speed diversity on constant Volt/Hz operation is investigated. In section V, we perform a comparison between constant Volt/Hz and conventional variable speed operation in terms of energy production.

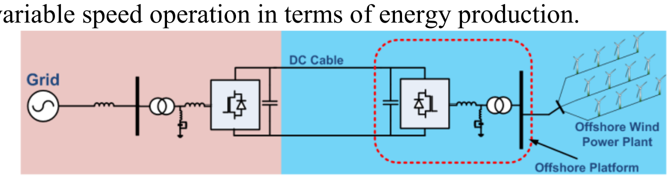

Figure 1: Offshore WPP connected via HVDC to the grid

II. WIND POWER PLANT CONTROL

In an offshore wind power plant, the wind flow is assumed to be more uniform compared to onshore. The surface roughness is very smooth compared to inland wind power plants where the wind flow may be diverted by different obstacles (hills, rocks, vegetation, etc.), thus creating non-uniform wind speeds among the turbines. Based on these uniform wind speeds, we operate the entire WPP at variable uniform wind speeds, we operate the entire WPP at variable frequency to match the WPP average wind speed $V_{w.ave}$ .Thus, the operation of individual wind turbines can be optimized.

A. Variable speed operation at constant V/Hz

1) Choosing the rated V/Hz

The *V/Hz* is a quantity that is proportional to the rated flux operating on the electromagnetic devices connected to the alternating currents within the collector systems. This includes the transformer and the electric machines.

We can choose the nameplate rating of the electric machine as the starting point. For an induction generator operating at constant voltage (i.e. 4160 V) and 60 Hz, the operation at constant *V/Hz* requires that the induction generator must be connected to a variable–voltage, variable-frequency voltage source which can deliver the rated value of *V/Hz*. The rated *V/Hz* ratio (K_r) of the generator can be determined as:

$$K_r = \frac{V_{gen.LL.rated}}{f_{rated}} \qquad (1)$$

Where $V_{gen.LL.rated}$ is the rated line to line voltage of the generator, and f_r is the rated frequency.

Thus, for the example given, the $\frac{V_{LL}}{Hz} = \frac{4160\,V}{60\,Hz} = 69.33\ \frac{V}{Hz}$. This value is set by the power converter at the HVDC connection at the offshore substation.

2) Tracking the $V_{w.ave}$

An example of the typical dependence of wind rotor power coefficient C_p on tip-speed ratio (*TSR)* is illustrated in Figure 2 shown below for different blade pitch angles [7].

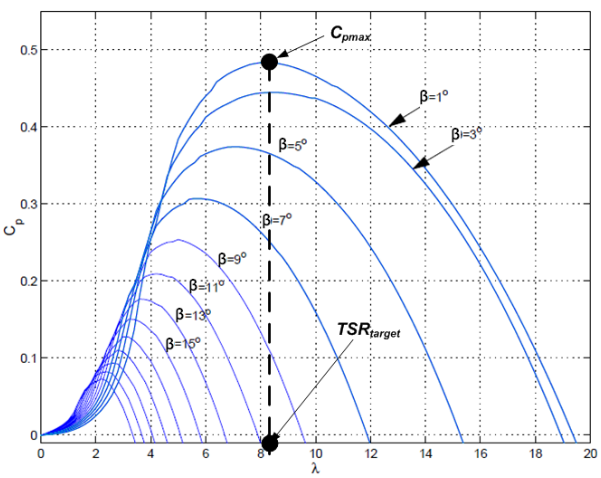

Figure 2: Cp versus TSR for a typical wind turbine

For an induction generator, the operating slip is usually very small (1% or less) in a high-power, high-efficiency induction generator. Thus, the operating rotational speed is practically proportional to the frequency of the generator.

The operation of a wind turbine is optimized so that we can operate the wind turbine at its C_{pmax} corresponding to the tip-speed ratio of TSR_{tgt}. For the C_p-*TSR* curve presented in Figure 2, the value of TSR_{tgt} is close to 8.

The operating frequency of the wind turbine generator can be computed as:

$$f = \frac{TSR_{tgt} V_{w.ave}}{R_{blade} K_{f.\omega}} \qquad (2)$$

and

$$K_{f.\omega} = \frac{4\pi}{p N_{gear}} \qquad (3)$$

Where:

f = frequency to be used (Hz) by the power converter of the offshore-side power converter.

$k_{f.\omega}$ = conversion factor from Hz to rad/sec

p = number of poles of the generator

N_{gear} = gear ratio of the gearbox used

The operating voltage of the output of the power converter at the offshore side of HVDC can be computed as:

$$V_{LL-HVDC} = K_r f n_S n_T \qquad (4)$$

where

n_S= substation transformer winding ratio

n_T = turbine (pad-mounted) transformer winding ratio

Thus, the voltage and frequency of the HVDC at the offshore must be commanded to follow the values $V_{LL\text{-}HVDC}$ and f.

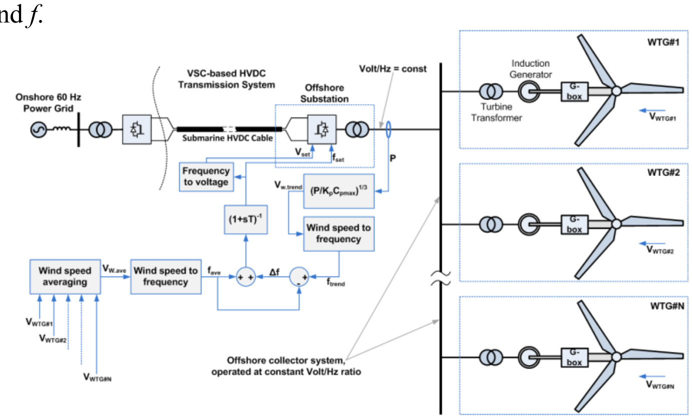

Figure 3: WPP control block diagram for V/Hz operation.

In Figure 3, an overall control diagram example is shown. The wind speed average ($V_{w.ave}$) is computed from the number of sensors located at different locations in WPP. By using at least three input sensors, the magnitude and direction of the $V_{w\text{-}ave}$ can be found. The operating frequency and its corresponding voltage commands can be computed and fed to the power converter offshore to set the voltage and frequency in the collector systems of the WPP. The constant Volt/Hz operation enables all transformers and induction generators to operate at rated flux to avoid magnetic saturation.

In the offshore WPP, the wind speed within the plant is more uniform than in a land-based WPP. The minor variation of wind speed at individual turbine with respect to the $V_{w.ave}$ will be minor. If a wind turbine received a significantly higher wind speed than the $V_{w.ave}$ used to determine the frequency and voltage, this wind turbine will generate higher output power and the output current may exceed the rated current. To protect individual wind turbines from operating at an overload conditions, the pitch control must be deployed.

III. Type I Wind Turbine – Induction Generator

Induction machines have been the workhorse of modern industry. Ever since its invention in 1883 by Nikola Tesla, this electric machine has been the favorite among other electric machines. A squirrel-cage induction machine operates without brushes; thus, the operation and maintenance are very simple. They have been used in WTG applications for years.

The concept of constant Volt/Hz control for a Type 1 wind turbine is illustrated in Figure 4. In this example, the turbine rated power is 2.5 MW. The target (or optimum) power is determined by the rotor maximum power coefficient (C_{pmax}). It is possible to operate the single turbine along the target power line by controlling the frequency and amplitude of the AC voltage on turbine terminals while maintaining a constant ratio between voltage and frequency.

Since the rated operating slip of a high-efficiency induction generator is very small (about 1%), the operating rotational speed is very close to the synchronous rotational speed. For wind turbine generators, this operating frequency can be computed from the average wind speed at the WPP as shown in equation 2. To operate the induction generator at rated V/Hz, the collector system voltage must be adjusted to operate according to equation 4.

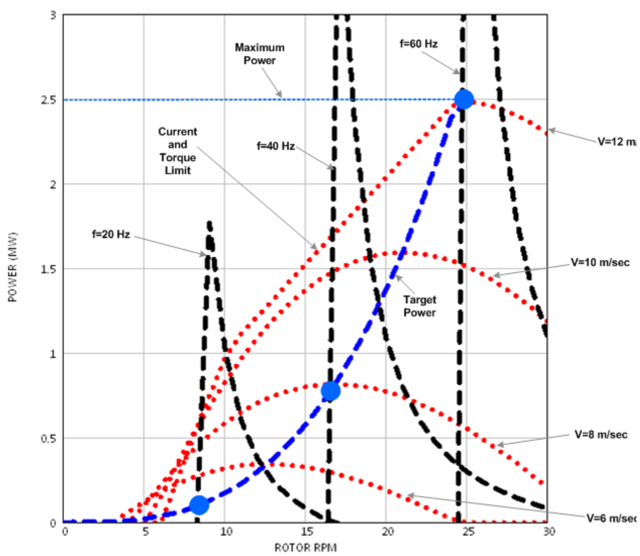

Figure 4: Constant V/Hz control

The turbine operates with zero pitch angle while following the target power line. The pitch control becomes active to limit the output current and to limit the turbine RPM at maximum value (about 24 RPM as shown in Figure 4), thus limiting the turbine power at the rated value of 2.5 MW. In this particular example, a 20-60 Hz frequency range covers the overall operational limits of the Type 1 wind turbine. The frequency must change linearly as a function of wind rotor RPM to provide such operation. Therefore, the frequency also changes linearly with wind speed according to Figure 5.

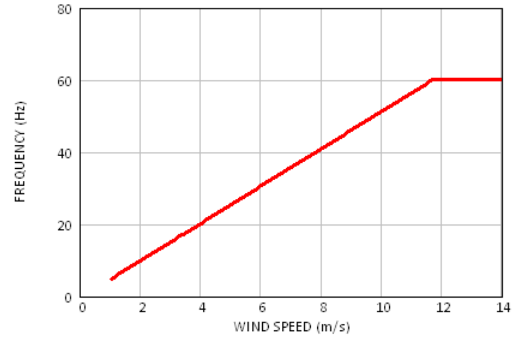

Figure 5: Frequency vs. wind speed at constant V/Hz operation

The power characteristics of the same example for a 2.5 MW wind turbine is shown in Figure 6 where the meshed surface represents the operational envelope of the generator, and the dotted lines represent the target power achieved at constant Volt/Hz control as a function of both electrical frequency and wind speed.

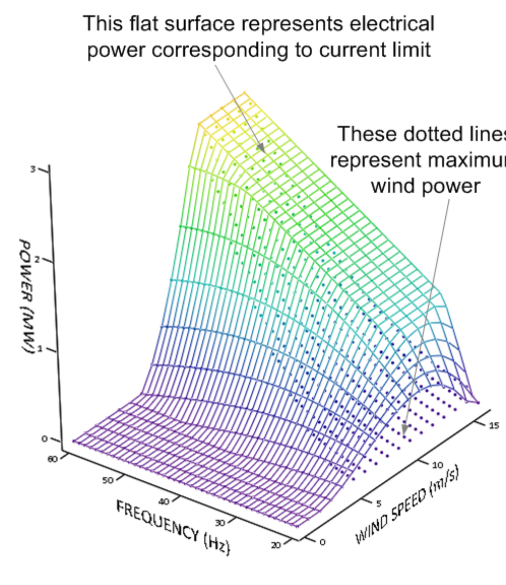

Figure 6: Power characteristics of Type 1 wind turbines

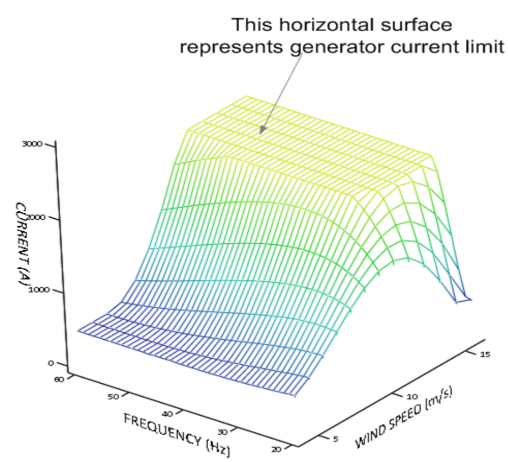

Figure 7: Current characteristics of Type 1 wind turbines

The flat portion of the surface represents the generator current limit at its rated value. It is identical to limiting the electromagnetic torque of ge nerator at rated level as well to ensure the integrity of both the electrical generator and mechanical components of the wind turbine. A care needs to be taken to operate the Type 1 wind turbine generator under the surface shown in Figure 6 by combining both pitch and Volt/Hz controls. In a similar manner, the operational envelope of Type 1 generator is shown in Figure 7, where the horizontal portion of the surface represents the generator operating at rated current (or rated torque).

IV. COMPARISON BETWEEN CONSTANT FREQUENCY AND CONSTANT V/HZ OPERATION

A. Single turbine operation

To demonstrate the advantage of the variable Volt/Hz system, the power curves of a single 2.5-MW wind turbine were calculated for the cases of variable and fixed frequency operations as shown in Figure 8.

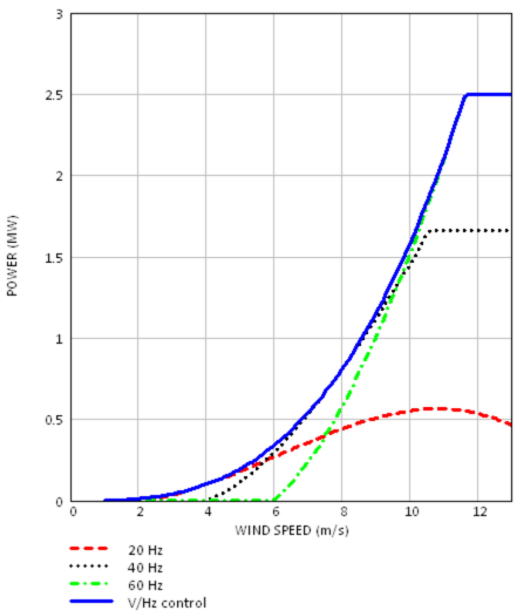

Figure 8: Power curve comparisons

As it can be observed from Figure 8, the variable Volt/Hz operation gives superior performance for the whole range of operational wind speeds, whereas fixed frequency operation can be optimized only for a narrower range of wind speeds.

B. Impact of non-uniformity of wind speeds within wind power plant

WPPs cover a very large area. Although the surface roughness across the sea water is much smoother than onshore WPPs, nevertheless, the wind speed within the WPP is not totally uniform. In this subsection, the impact of wind power variation from one turbine to another will be explored. The impact on the energy yield and the possible control strategy will be explored.

The power curves shown in Figure 8 are used to determine the total power output of the large offshore WPP that consists of 100 turbines (250-MW total power rating). A single VSC-based HVDC converter sets both AC voltage and frequency that is the same for all Type 1 WTGs. If the wind speed was uniformly similar across the whole WPP, then each individual WTG would be operating along the solid-line power curve shown in Figure 8. In reality, there is always some wind speed diversity across the WPP. The wind speed at each individual wind turbine will be distributed randomly around some average value. We assume for simplicity that at any given instance in time, the wind speed across the whole WPP is distributed according to normal distribution, as shown in the Figure 9 example for an average wind speed $V_{ave} = 8\frac{m}{s}$ and standard deviation $\sigma = 1$.

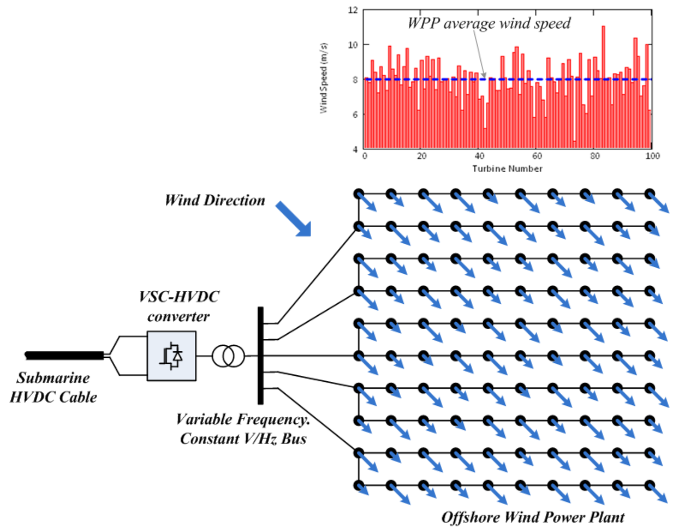

Figure 9: Wind speed diversity across WPP (N=100)

The normal probability density function for wind speed deviation ΔV[m/s] from the mean value V_{ave}[m/s] for the whole WPP:

$$\boldsymbol{f}(\Delta \boldsymbol{V}) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{\Delta V^2}{2\sigma^2}} \qquad (5)$$

Where σ[m/s] is the standard deviation of wind speed from its mean value.

The wind speed at each individual wind turbine then can be calculated using a cumulative distribution function corresponding to normal probability density:

$$\boldsymbol{F}(\Delta \boldsymbol{V}) = \frac{N}{2}\left[1 + \boldsymbol{erf}\left(\frac{\sqrt{2}}{2}\frac{\Delta V}{\sigma}\right) \boldsymbol{csgn}(\boldsymbol{\sigma})\right] \qquad (6)$$

Where erf and $csgn$ are Gauss error and signum functions respectively, and N is total number of wind turbines connected to the same frequency bus.

The probability density function for wind speed deviations from the mean across the WPP is shown in Figure 10 for different values of standard deviation wind speed (σ=0, 1, 2 and 3 m/s). An ideal, uniform, WPP will have σ=0m/s, while a very diverse onshore WPP covering a very large area may have σ=3m/s. Larger standard deviation σ indicates a large diversity of wind speeds at the WPP.

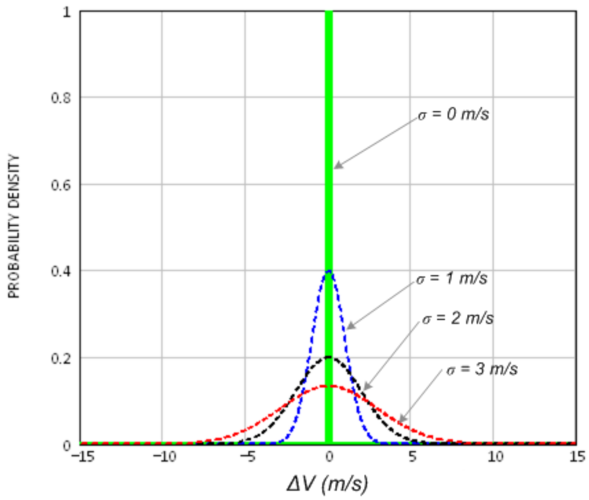

Figure 10. Normal probability density of wind speed deviations

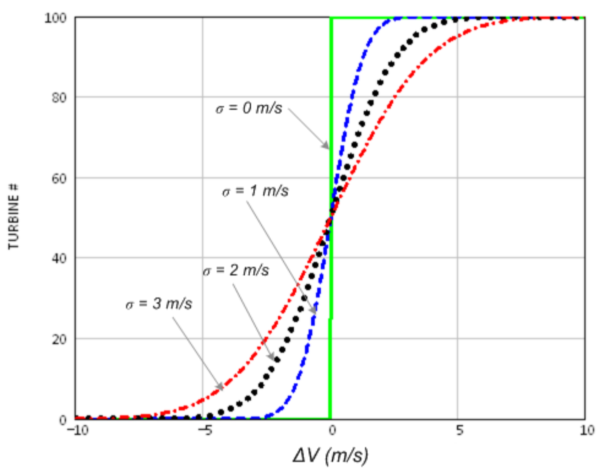

Figure 11: Distribution of wind speed deviations

This approach assumes symmetrical distribution of wind speeds above and below the average value, as shown in the Figure 11 example for a WPP consisting of 100 wind turbines (*N*=100). Thus, WTG #50 is at its average wind speed V_{ave}. The wind speed for each individual turbine can then be determined from Figure 10 and Figure 11:

$$\boldsymbol{V_k = f(V_{ave} + \Delta V_k, \sigma, k)} \qquad (7)$$

Where k is the turbine index number, and ΔV_k is the deviation of wind speed from the mean at turbine #*k*.

Power production of each individual wind turbine depends on its wind speed and is determined from power curves shown in Figure 8 for each operational frequency. The total power output of the WPP can then be calculated as:

$$\boldsymbol{P_{total}(V_{ave}.\sigma.f) = \sum_{k=1}^{100} P(f, V_k)} \qquad (8)$$

The total power output of the WPP is then a function of average wind speed for the whole WPP, wind speed standard deviation σ, and electrical frequency f. The collector system frequency f is controlled to be proportional to the average wind speed according to equation 2, and the voltage is controlled to maintain the rated V/Hz according to equation 4.

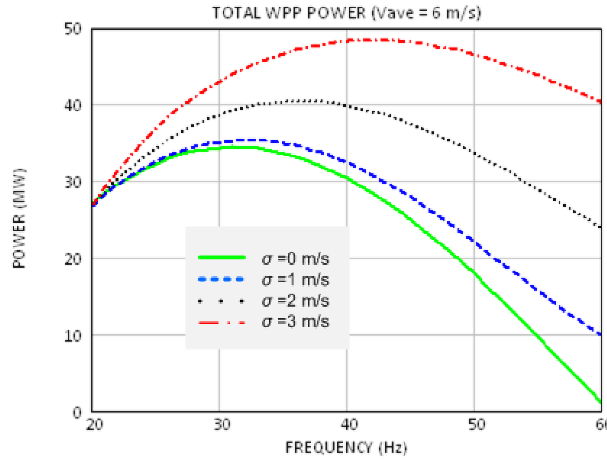

Figure 12: Total WPP power at 6 m/s average wind speed

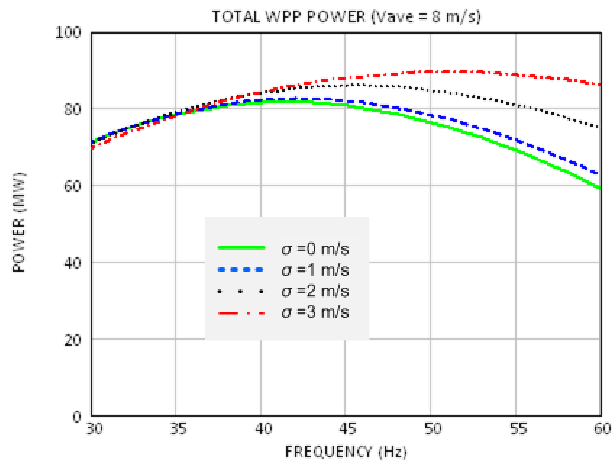

Figure 13: Total WPP power at 8 m/s average wind speed

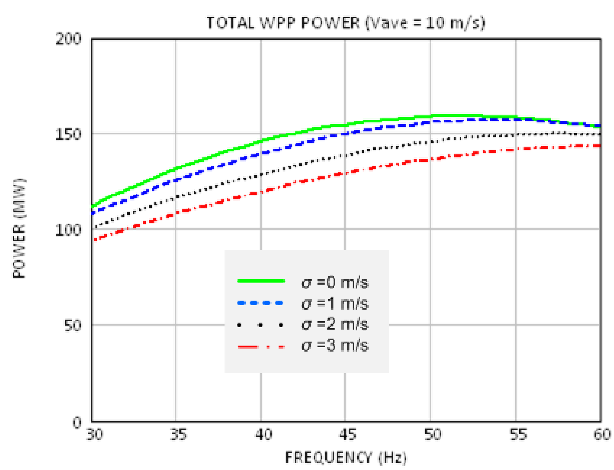

Figure 14: Total WPP power at 10 m/s average wind speed

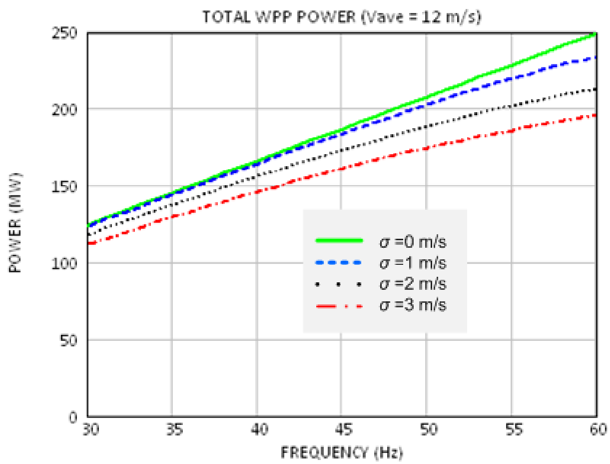

Figure 15: Total WPP power at 12 m/s average wind speed

Some calculation results are shown in Figure 12 through Figure 15 (A, B, C and D) for four different average wind speeds (V_{ave}= 6, 8, 10, and 12 m/s) and four standard deviations (σ=0, 1, 2, and 3 m/sec) respectively. It can be seen from these figures that for every combination of V_{ave} and σ, there is an optimum electrical frequency that produces maximum total WPP power. The only exception is in Figure 15 when all turbines operate at the flat portion of the power curve. It is important to note that cases where $\sigma = 0$ are not realistic since there is always wind speed diversity from turbine to turbine in the same WPP. The $\sigma = 0$ cases are shown here for reference and comparison purposes only.

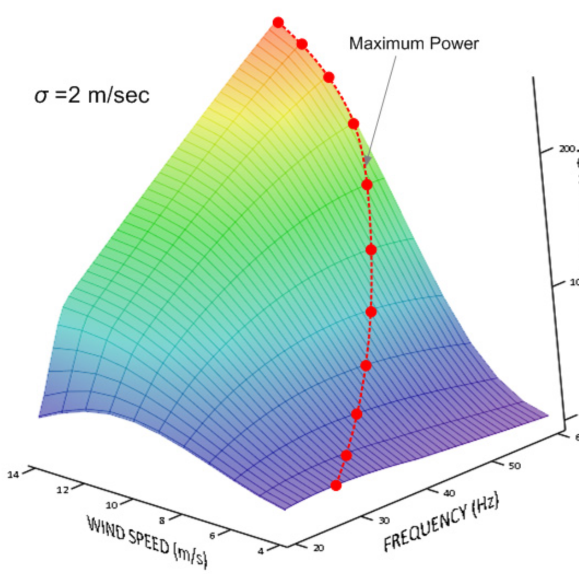

Figure 16: Optimum frequency control

C. Energy production comparison

The aggregate power curves for the whole WPP are needed for annual energy production estimation purposes. Such calculated power curves are shown in Figure 17 and Figure 18 for the cases of fixed 60 Hz and variable frequency (constant V/Hz) respectively. These curves were calculated for the same example WPP consisting of *N*=100 Type 1 WTGs for different values of σ. As can be seen in both figures, the larger values of σ cause larger deviations of aggregate WPP power from the single turbine power curve.

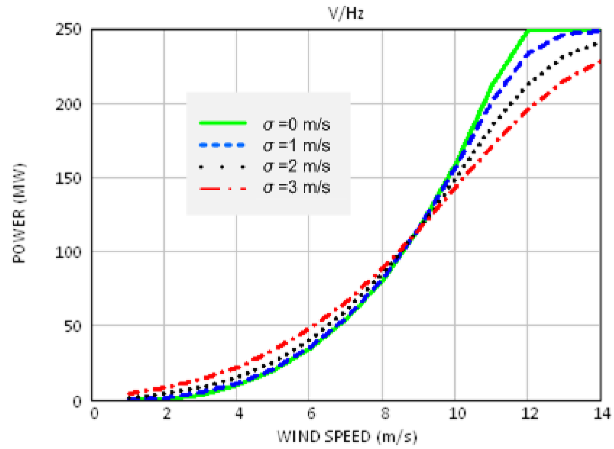

Figure 17: Aggregate WPP power at fixed 60 Hz

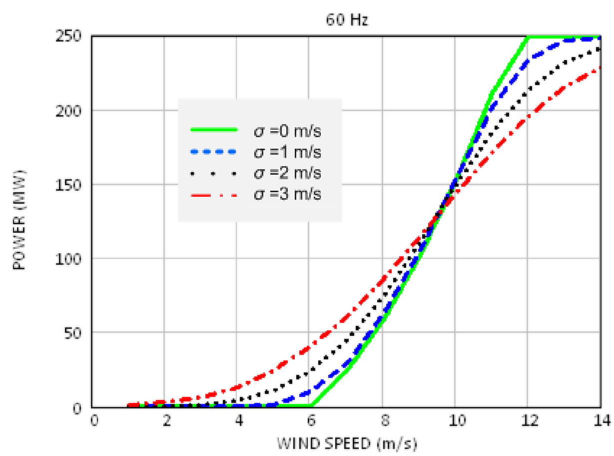

Figure 18: Aggregate WPP power at Volt/Hz control

The annual energy production can be calculated using power curves shown in Figure 17 and Figure 18, and a Weibull wind speed probability density function:

$$W(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \qquad (10)$$

Where k and c are the Weibull shape and scale parameters respectively. The annual energy production for each value of σ can then be calculated as:

$$E(\sigma) = 8760hr \int_0^{Vmax} P(\sigma, V) W(V) dV \qquad (11)$$

Where $P(\sigma, V)$ is the aggregate WPP power curve determined from Figure 17 and Figure 18.

The resulting annual energy production values are shown in Figure 18 for the cases of 60 Hz and variable frequency operation for different values of standard deviation of wind speeds (the values of Weibull factors k=2 and c=9 m/sec were used). The gains in energy production are higher for smaller values of σ. For example, the variable frequency operation produces about 12-13% more energy compared to 60 Hz operation for a case when $\sigma = 1$.

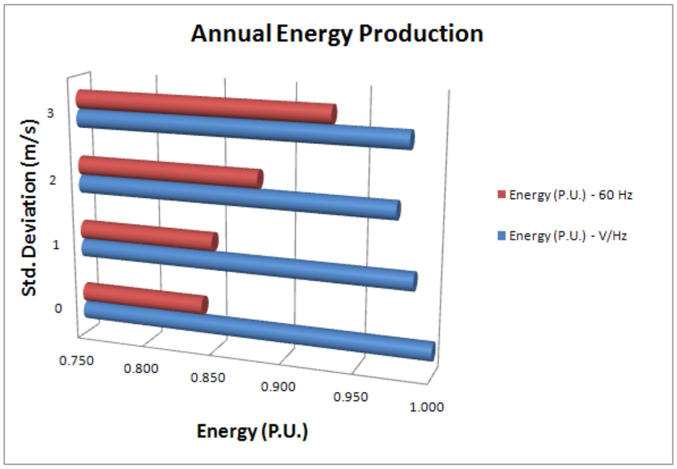

Figure 19: Energy production comparison

V. COMPARISON WITH VARIABLE SPEED OPERATION

We conducted the analysis to compare the annual energy production between a Type 1 WPP with V/Hz control and constant 60 Hz WPP using Type 3 or Type 4 variable-speed wind turbines. The layout of offshore VSC-HVDC interconnected WPPs using Type 4 topology is shown in Figure 20 below.

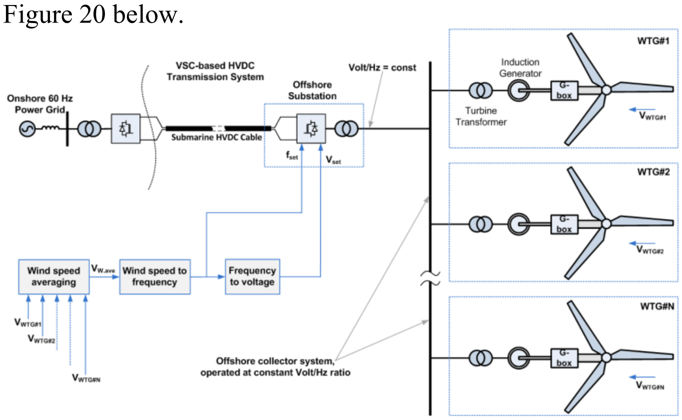

Figure 20: A WPP with variable-speed Type 4 wind turbines

The aggregate power curves for different values of $\sigma$are shown in Figure 21. The annual energy production was calculated using the same Weibull parameters. A comparison of annual energy outputs with Type 1 WPPs operating at fixed 60 Hz and variable frequency (constant V/Hz ratio) is shown in Figure 22. As expected, the conventional variable-speed operation offers higher energy production. This is more obvious for the sites with higher wind speed diversity (or higher values of σ). However, for lower σ, the difference between V/Hz and variable-speed options becomes small (less than 3% for $\sigma = 1\, m/\text{sec}$). This fact creates a promising opportunity for the proposed V/Hz control for Type 1 offshore WPPs at considerable distances from the shore.

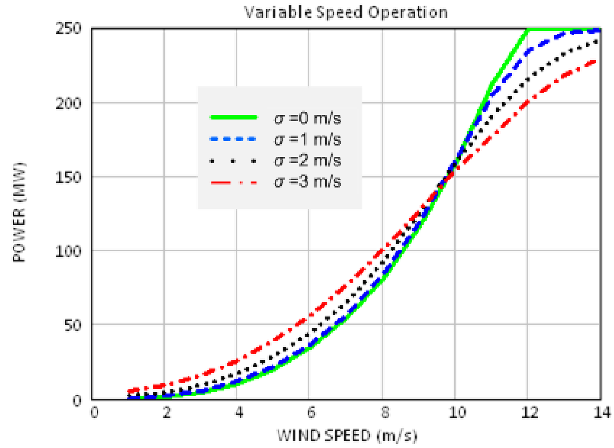

Figure 21: Aggregate power curves for Type 4 WPPs

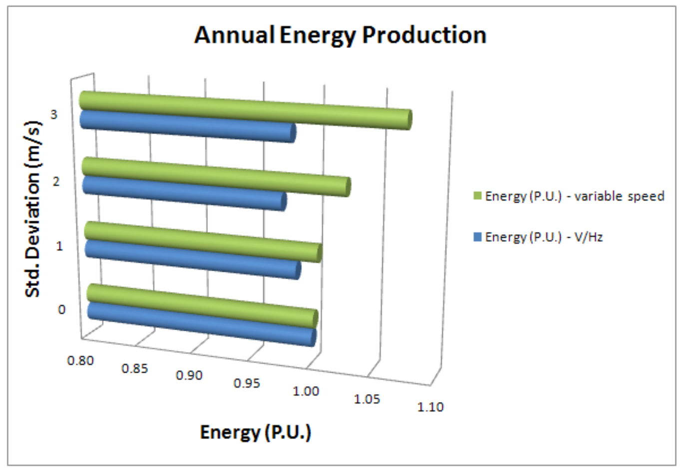

Figure 22: Energy production comparison with variable speed option

VI. ONSHORE WPP DATA ANALYSIS

Wind speed data from large onshore WPP consisting of 100 wind turbines have been analyzed to determine the wind speed distributions among individual wind turbines.

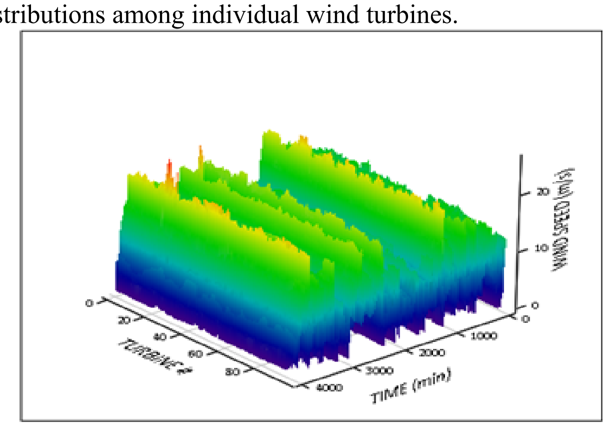

Figure 23: 10-min wind speed data for an onshore WPP

A nearly 1-month time series of 10-min average wind speed data for individual wind turbines in large onshore WPP consisting of 100 units is shown in Figure 23. The analysis showed that normal distribution fits the distribution of wind speeds among individual wind turbines for each 10-min interval. The mean σ over the period of observation is close to 1 m/s as can be seen in Figure 24.

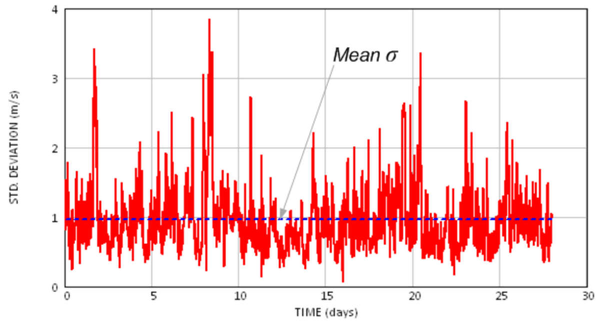

Figure 24: Std. deviation of wind speeds for 100 wind turbines

A sensitivity of the mean value of σ to the number of wind turbines for the same WPP is shown in Figure 25. It is expected that the standard deviation in an offshore WPP will be smaller than the standard deviation of the onshore WPP presented in this section.

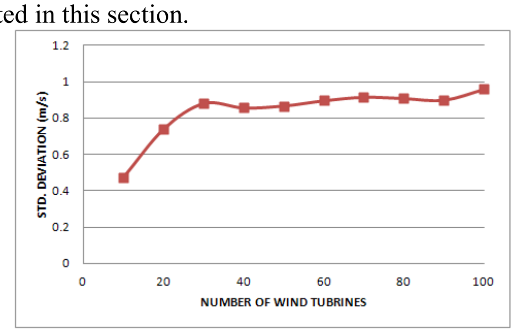

Figure 25: Std. deviation vs. number of wind turbines

VII. Conclusions and Future Plans

In this paper, we have investigated the operation of an offshore WPP connected to the grid via an HVDC-VSC system. The offshore substation is operated in variable frequency mode in a rated V/Hz ratio to allow operation of the WPP in variable speed and near its optimum value of maximum C_p. In this paper, the diversity of WPPs is analyzed and a comparison of annual energy production of various WPP control options is performed. It was shown that estimated annual energy production of Type 1-based WPPs in constant V/Hz operation is close to the output of Type 3 or 4 WPPs in conventional variable-speed operation. It is expected that the standard deviation in an offshore WPP will be smaller than the std dev of the onshore WPP presented in section VI.

Future plans include detailed analysis of the proposed system for capital cost and cost of energy (COE) in offshore applications. Also, the same authors are working on a similar constant V/Hz operation concept for Types 2, 3, and 4 wind turbines. The benefits may include simpler turbine topologies, smaller power converters, and better electrical efficiencies, etc.

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IX. Biographies

Vahan Gevorgian (M'97) graduated from the Yerevan Polytechnic Institute (Armenia) in 1986. During his studies he concentrated on electrical machines. His thesis research dealt with doubly-fed induction generators for stand-alone power Systems. He obtained his Ph.D. degree in Electrical Engineering Dept. from the State Engineering University of Armenia in 1993. His dissertation was devoted to a modeling of electrical transients in large wind turbine generators.

Dr. Gevorgian is currently working at the National Wind Technology Center (NWTC) of National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA, as a research engineer. His current interests include modeling and testing of various applications of wind turbine based power systems. He is a member of IEC61400-21 wind turbine power quality standard development group.

Mohit Singh (M'2011) received his M.S. and Ph.D. in Electrical Engineering from the University of Texas, Austin in 2007 and 2011 respectively. His research is focused on dynamic modeling of wind turbine generators.

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Eduard Muljadi (M'82-SM'94-F'10) received his Ph. D. (in Electrical Engineering) from the University of Wisconsin, Madison. From 1988 to 1992, he taught at California State University, Fresno, CA. In June 1992, he joined the National Renewable Energy Laboratory in Golden, Colorado. His current research interests are in the fields of electric machines, power electronics, and power systems in general with emphasis on renewable energy applications. He is member of Eta Kappa Nu, Sigma Xi and a Fellow of the IEEE. He is involved in the activities of the IEEE Industry Application Society (IAS), Power Electronics Society, and Power and Energy Society (PES).

He is currently a member of various committees of the IAS, and a member of Working Group on Renewable Technologies and Dynamic Performance Wind Generation Task Force of the PES. He holds two patents in power conversion for renewable energy.