Application of Boost Converter and Superconductive Coil Combination in Variable Speed Wind Energy System

M. Monfared, *Student Member, IEEE,* and G. B. Gharehpetian, *Member, IEEE*

***Abstract*-- In this paper, after a brief review of the variable speed wind turbines, an advanced idea for wind farms is presented and studied. The suggested system is a combination of recently developed technologies along with the innovative application of the superconductive coil. The application of the superconductive coil in the boost converter topology is suggested in this paper. Besides, the suggested system has the capability of DC power transmission to a proper connection point without using any additional equipment. This feature reduces the transmission costs, especially the cables cost.**

***Index Terms*—Variable speed wind turbine, boost converter, superconductive coil.**

I. INTRODUCTION

Due to an increasing demand for renewable energy resources, the wind energy has received more attention recently. Therefore, new improved strategies regarding the wind energy production, transmission and management should be developed in order to increase the efficiency, reliability and power quality as well as to decrease the overall system cost. Advanced strategies are most based on the effective utilization of semiconductor devices, energy storage systems and permanent magnet synchronous generators. Besides, the variable speed operation of the wind turbine using the power semiconductor converters becomes more attractive day by day. It is well known that any control of the turbine speed increases the wind power capture efficiency [1, 2]. In this paper, an advanced idea for wind farms is presented and studied in details. Besides, the use of superconductive coil in the boost converter topology is suggested. So, in the following sections, first, the present techniques and then the suggested strategy for variable speed wind turbines are presented. The suggested system includes a multi-pole permanent magnet synchronous generator. This generator eliminates the need for gearbox whereas it improves the efficiency, reduces the noise and leads to more money saving [3]. The idea of using superconductive coils to link wind farms has been illustrated to successfully reduce the wind turbine output fluctuations and the capacity of the converter system and improve the system reliability [4]. On the other hand, usually, the AC bus of wind farms is weak and the connection is not reliable and effective. The suggested system has the capability of DC power transmission to a proper connection point without using any additional equipment. This feature reduces the transmission cost. Also, DC integration of wind farm generation units has several other benefits over the AC integration [5].

II. VARIABLE SPEED WIND TURBINES, PRESENT

The annual captured wind power of the variable speed wind turbines is about %5 more than the fixed speed turbines. In addition, in variable speed wind turbines the active and reactive powers can be controlled fast and easily and THD can be improved. Also, the generator is insulated from the power grid by a DC link which reduces the mechanical stresses and electrical flickers considerably and strengthens the system against a wide range of voltage and frequency deviations. It must be noted that there is no generator torque strike after a fault occurrence and the ability to control the reactive power lets the wind generation unit to control the grid voltage [1, 2]. In spite of all above mentioned benefits, the need for power semiconductor converters is the major disadvantage of these systems. These converters increase the number of equipments, the system cost and the control complexity. Variable speed operation means that the rotor mechanical frequency is decoupled from power grid frequency. As mentioned before, this idea can be implemented by power semiconductor converters such as AC-DC-AC converters. Although, Doubly Fed Induction Generators (DFIG) are quasi-variable speed generators and let a limited range of rotor speed variations but this paper focuses on full variable speed operation from the start-up up to the shut-down speeds. This system is depicted in Fig. 1. As it can be seen, a Voltage Source Converter (VSC) converts the power captured by the generator into a DC link and another VSC converts and controls the DC power into the AC power. In this topology, usually the generator side converter controls the generator electromagnetic torque by means of vector control algorithms; also it supplies the induction generator magnetizing current. The grid side converter controls the active and reactive powers and maintains the THD as low as possible. The DC link capacitor maintains the energy equilibrium. A proper control system adjusts the DC link voltage level in a specified band [1, 2, 6]. The other topology, shown in Fig. 2, is to replace the induction generator and the generator side VSC by a

---

Authors are with the electrical engineering department, Amirkabir University of Technology, Tehran 15914, Iran. (phone: +98-21-64543366; e-mail: {m.monfared, grptian}@aut.ac.ir).

synchronous generator and a simple diode bridge rectifier. Here, the DC link voltage can be easily regulated by controlling the generator field. Although the cost and the control requirements of the generator increase but the rectifier is very cheaper and does not require any control hardware and software [7].

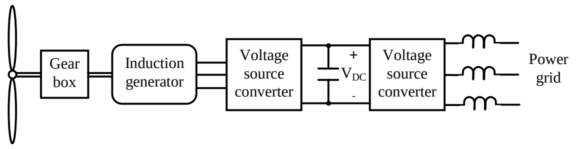

Fig. 1. Variable speed wind turbine with induction generator

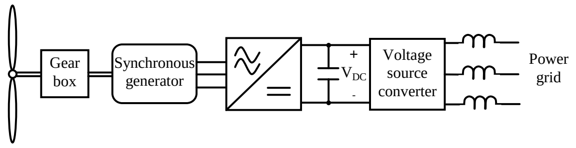

Fig. 2. Variable speed wind turbine with synchronous generator

III. Suggested Variable Speed Wind Turbine System

The suggested system, shown in Fig. 3, is a combination of recently developed technologies and the innovative application of the superconductive coil. The multi-pole Permanent Magnet (PM) synchronous generator, shown in Fig. 3, eliminates the gearbox in the drive train. Several manufacturers have made these generators technically and economically effective and some of them, up to 3.6 MW, have been installed and are operating successfully [3]. The benefits of these generators are their smaller size, lighter weight and higher efficiency. The effective utilization of PM materials as well as the elimination of the rotor windings not only reduces the losses but also simplifies the control algorithm. It must be noted that direct-drive technology has simpler and robuster mechanical structure and quieter operation than the gearbox-coupled technologies. Evidently, it is due to the elimination of the rotor windings and the gearbox [3, 8]. Three capacitors on the generator terminals supply its capacitive current, thereby the generator power capacity increases as well as its voltage stabilizes against its current variations. The generated AC power is converted to DC power by a diode rectifier. This rectifier is simple and robust and there is no need for any kind of control system. Obviously, it is very cheaper than the voltage source converters. Due to the turbine speed variations, the rectifier output voltage has variations, so a boost chopper amplifies the rectified voltage to the DC link voltage level. Controlling the boost chopper current, the generator electromagnetic torque and consequently its speed can be regulated. The middle point of the symmetric DC link capacitor bank is grounded. The grounding reduces the electromagnetic interferences considerably. In the DC link a brake chopper dissipates the extra energy whenever the DC link voltage exceeds its maximum allowed value, otherwise, this energy may cause damages to the equipments. The voltage source converter is a six-pulse converter which converts the DC electric energy into the AC power and controls the active and reactive power exchanges with the grid. Fig. 4 depicts how a current controlled VSC scheme realizes the output active and reactive powers of the wind generation system. To limit the harmonics generated by the VSC switching, an appropriate AC filter has been installed between the VSC and the AC grid. The mechanical-aerodynamic model of the wind turbine is based on the model developed in [9].

A. Boost converter with superconductive coil

The rectified voltage can be varied during the generator speed variations. The boost converter maintains the DC link voltage at its desired value. This regulation is achieved by controlling the converter switch conduction time in each switching period (D). The constant DC voltage leads to increased efficiency and more efficient utilization of the semiconductor devices. The basic equations in a voltage mode boost converter for continuous operation is summarized in table 1, where R and f_s are the load equivalent resistance and the switching frequency, respectively [10].

Table I
Basic equations of voltage mode boost converter in continuous operation

Frequency of 2nd order pole	$\frac{(1-D)}{2\pi LC}$
Frequency of RHP zero	$\frac{(1-D)^2 R}{2\pi L}$
DC gain: $\frac{V_o}{V_i}$	$\frac{1}{(1-D)}$
Inductor current ripple: ΔI_L	$\frac{V_i D}{f_s L}$

One can see in table 1 that the boost converter behaves as a second order system which has an extra zero in right half plane (RHP). This zero makes the system non-minimum phase which is undesirable in voltage regulators; because the output voltage variation cannot be followed by the controller. As shown in Fig. 3, the energy storage device has the essential role in the boost converter operation. In each switching period and during the switch on state, energy is stored in the inductor magnetic field and then during the switch off state, this energy is transferred to the DC link capacitor bank. If a superconductive coil is used for this energy transfer operation, the energy handling capability and the efficiency will increase considerably. This kind of energy storage devices has been suggested to improve the power system dynamics and to compensate the industrial loads. Especially when the energy capacity is low, high temperature superconductors can be used which makes the system even more cost effective [11]. Although the idea of employment of superconductive energy storage devices in the DC link is not new [11], but, the idea of using these devices in the AC-DC-AC topology for DC integration of wind turbines of a wind farm is presented recently [4]. The system presented in [4] needs superconductive coils with very high energy capacities; therefore, there are severe technical and economical limits. In the suggested system of this paper, each wind turbine boost converter is equipped with a superconductive coil as its electromagnetic energy storage device.

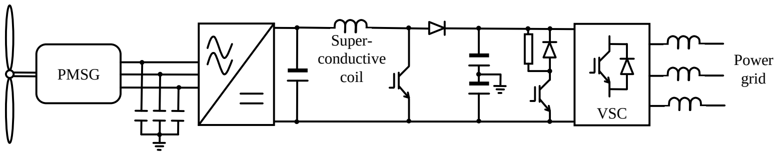

Fig. 3. Suggested variable speed wind turbine, suggested system

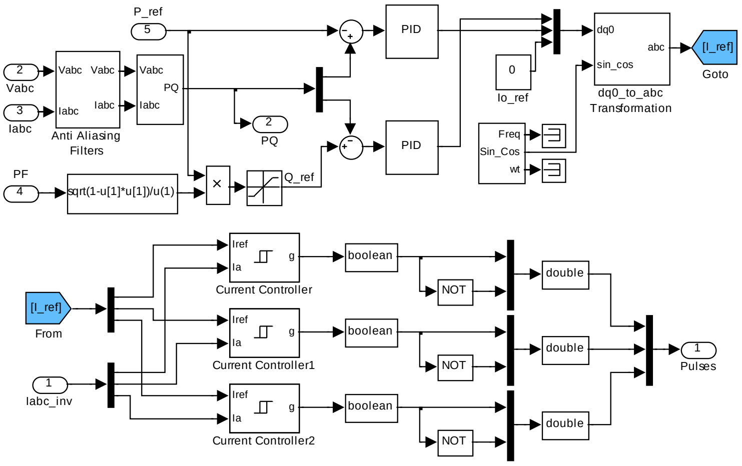

Fig. 4. VSC current control scheme

So their energy capacity is low and high temperature superconductors can be used leading to practical and cost effective systems. The system suggested in [4] needs coils with several ten MJ energy capacity but the capacity of devices used in this paper is less than some hundred kJ.

Considering table 1, the natural frequency and damping factor of a boost converter can be calculated as follows:

$$\xi = \sqrt{\frac{L}{C}}\frac{1}{2R(1-D)}, \omega_m = \frac{(1-D)}{\sqrt{LC}} \tag{1}$$

As it can be seen in Eq. 1, large values of L decrease the system frequency and the ripple components of the state variables. But in case of large values of L, the RHP zero moves toward the origin and becomes dominant. This non-minimum phase dominant zero defects the control system. To overcome this problem, as shown in Fig. 5, the superconductive coil current is measured and used in an inner current control loop inside the DC link voltage control loop. However, with very large values of L, superconductive coil current ripple (ΔI_L) may become very small, compared to its average value, so the inner current control loop may fail to work properly. Therefore it is clear that the DC link voltage controller must be designed exactly, also the capacity of the superconductive coil should be selected carefully according to the above mentioned limits. Fig. 6 shows how the suggested strategy lets integrate the generators of a wind farm through a common DC link.

B. *Power control technique*

In this paper, the VSC current is controlled using the decoupled *dq* method [7]. Variables in the *abc* three phase coordinates are transformed into the *dq* reference frame rotating at synchronous speed. In three phase balanced system, the instantaneous active and reactive powers can be described by the Eq. (2), as follows:

$$Q = \frac{3}{2}(V_d I_q - V_q I_d), P = \frac{3}{2}(V_d I_d + V_q I_q) \tag{2}$$

Where V_d, V_q, I_d and I_q are wind turbine voltages and currents at d and q axis respectively. Assume that V_q is the magnitude of the instantaneous voltage at the wind generation system ($|V_o|$) and V_d is always zero, then the Eq. (2) can be rewritten in the following form [7]:

$$Q = -\frac{3}{2}|V_o|I_d, P = \frac{3}{2}|V_o|I_q \tag{3}$$

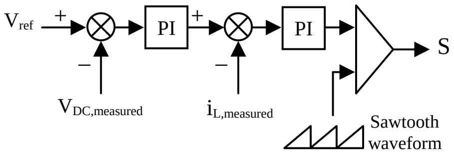

Fig. 5. Voltage mode boost chopper controller

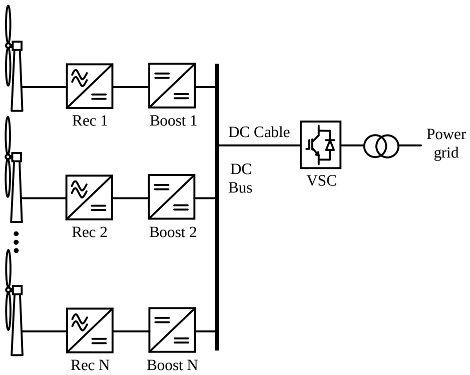

Fig. 6. Integration of generators of wind farm through common DC link

$|V_o|$ remains at the level of the grid AC voltage, therefore P and Q can be controlled separately by specifying the reference values of I_q and I_d, respectively. Fig. 4 shows the control scheme. The corresponding firing pulses are produced by a hysteresis current controller. The reference values for P and Q are determined according to the VSC control strategy. The main purpose of the active power control strategy is to capture the maximum mechanical power from the wind. The reactive power is controlled in order to adjust the power factor or to control the system voltage. It is always desired that the wind turbines operate near unity power factor to prevent the disturbances in nearby power network. So, the reference value of the reactive power can be calculated from the reference values of the active power and the power factor by Eq. (4).

$$Q_{ref} = P_{ref} \frac{\sqrt{1-PF^2}}{PF} \tag{4}$$

The reactive power limits of the wind turbine are mainly determined by the VSC ratings and can be described by Eq. (5), where S_{vsc} and P_{vsc} are the VSC rating and the output active power, respectively.

$$Q_{\text{limit}} = \pm\sqrt{S_{vsc}^2 - P_{vsc}^2} \tag{5}$$

C. Maximum power point tracking

The output power curves versus the turbine rotational speed for different values of wind speed are depicted in Fig. 7. These curves imply that the maximum output power for each wind speed can be achieved at a particular turbine speed. These curves are available by turbine manufacturers. So, in order to capture the maximum power, for any wind speed, the reference value of the VSC active power must be adjusted according to these curves. The obtained value from these curves should be multiplied by the generator and converters overall efficiency, η, as follows:

$$P_{ref} = \eta P_{M,\max} \tag{6}$$

Fig. 8 shows how the operation of a variable speed wind turbine can be divided into two regions. Whenever the wind speed <u>and</u> the output power are both below their rated values, the power optimization is activated. As a result, for any wind speed, the shaft speed will be controlled in order to capture the maximum power, as shown in Fig. 7. In any wind speed, the turbine power coefficient (C_P) is kept at its maximum value. If the wind speed <u>or</u> the output power exceeds its rated value, the power limitation is activated in order to limit the output power to its nominal value by adjusting the shaft speed [12].

IV. SIMULATION RESULTS

The suggested system, simulated in MATLAB/Simulink is illustrated in Fig. 15. The wind turbine power is 1200 kW and its characteristic curve is shown in Fig. 8. Permanent magnet synchronous generator has 40 pole pairs and the nominal rotor speed is 30 rpm. The capacity of the superconductive coil is determined by its maximum current. This current is obtained for the minimum rectifier output voltage which occurs for minimum wind speed, i.e. start-up speed. Hence, the capacity of superconductive coil is chosen to be 150 kJ. Figures 9 and 10 show the dynamic performance of the DC link voltage control loop in response to the step changes in the input voltage. An increase in the input voltage initially causes an increase in the DC link voltage which is then compensated by a decrease in the input current. Also, following a decrease in the input voltage, DC voltage controller again adjusts the superconductive coil current to balance the active power flow. In the next simulation, the wind speed shown in Fig. 11 is applied to the model. This wind speed pattern lets us to easily obtain the curves of the output power and DC link voltage variations versus wind speed, depicted in figures 12 and 13. Obviously, Fig. 12 complies exactly with the wind turbine characteristic curve which is presented in Fig. 8. This implies that the VSC power controller acts perfectly. Also, Fig. 13 shows that the DC link voltage is robust against the wind speed variations. Fig. 14 shows the performance of the hysteresis current control loop for the rated output power. In the other study, the fluctuating wind speed, as shown in Fig. 16, is applied to the model and the output power and the DC link voltage are recorded in figures 17 and 18. Fig. 17 shows the effectiveness of the power control strategy. Moreover, DC link voltage variation is also limited in an acceptable band.

V. CONCLUSION

In this paper, an advanced idea for wind farms has been presented. The boost converter and superconductive coil combination have been studied. It is shown that the suggested system has the ability of the DC power transmission without using any additional equipments or cost.

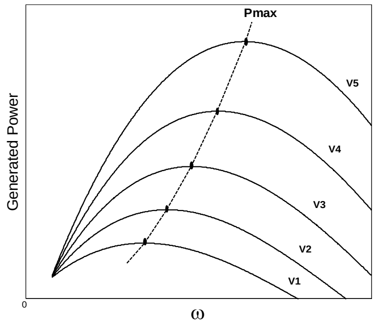

Fig. 7. Output power curves versus turbine rotational speed for different values of wind speed

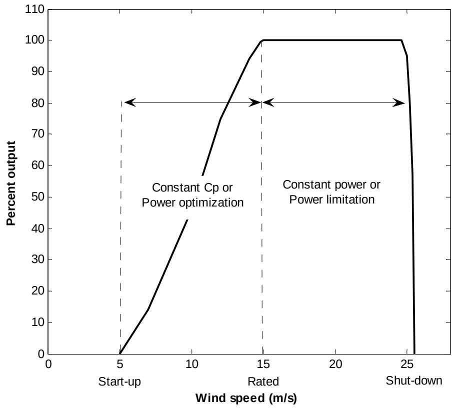

Fig. 8. Operation regions of variable speed wind turbine

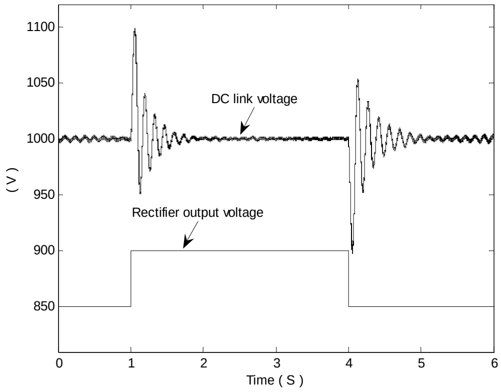

Fig. 9. Dynamic performance of DC link voltage control loop in response to step changes in input voltage

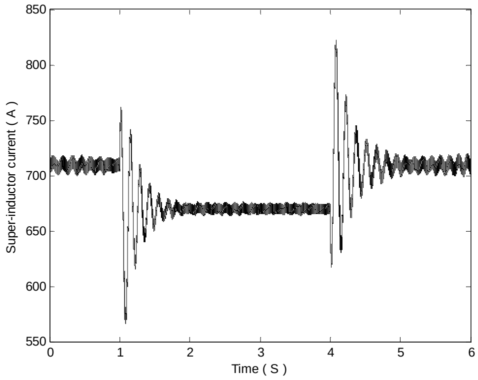

Fig. 10. Dynamic performance of DC link voltage control loop in response to step changes in input voltage

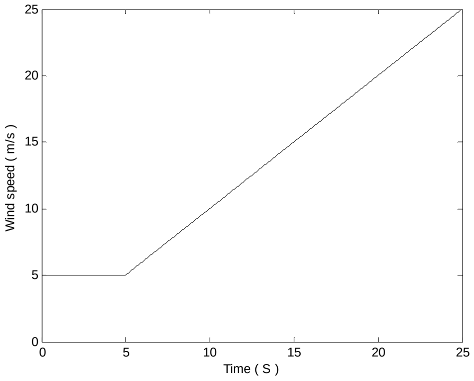

Fig. 11. Input wind speed variations versus time

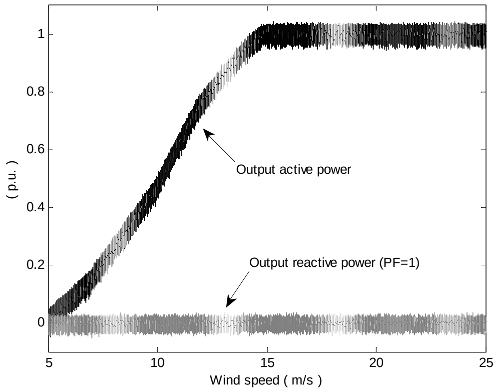

Fig. 12. Active power curve and output reactive power versus wind speed

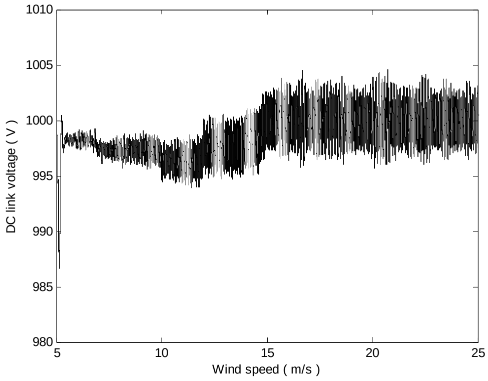

Fig. 13. DC link voltage versus wind speed

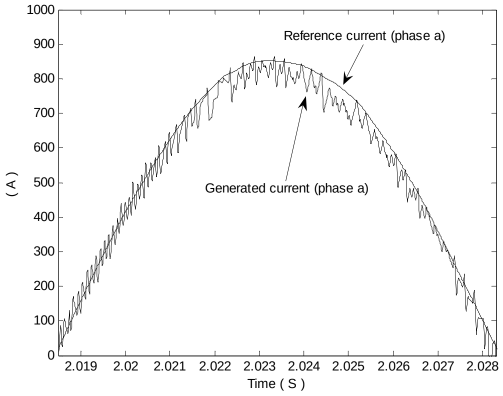

Fig. 14. Hysteresis current controller performance

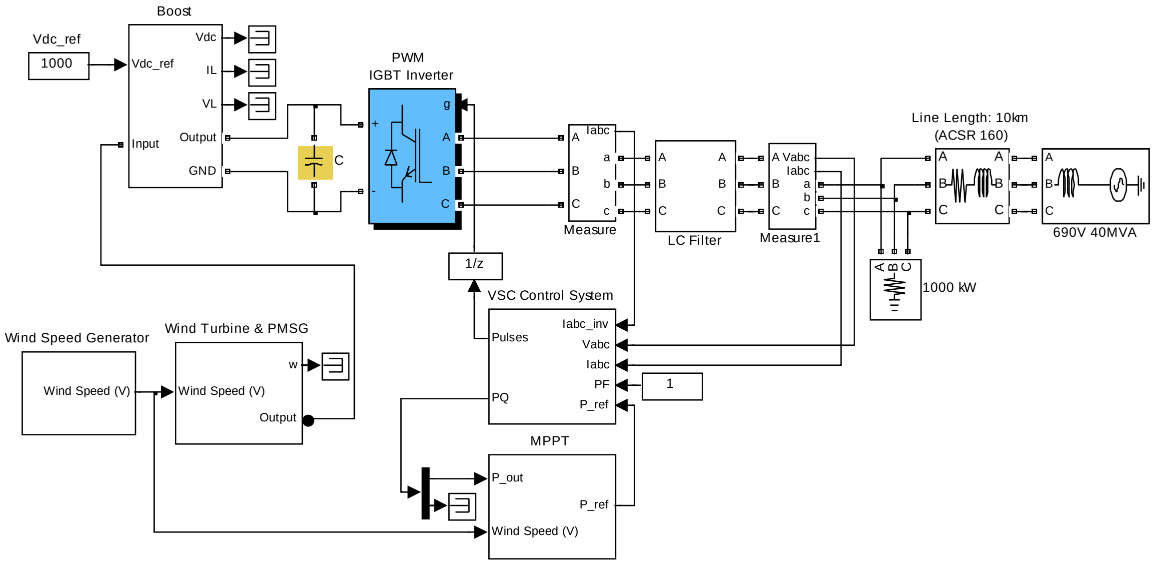

Fig. 15. MATLAB/Simulink model of suggested system

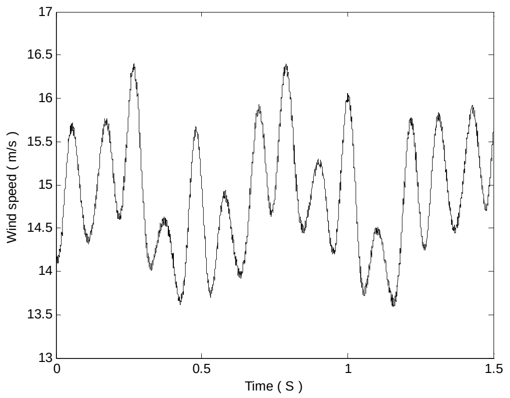

Fig. 16. Fluctuating wind speed

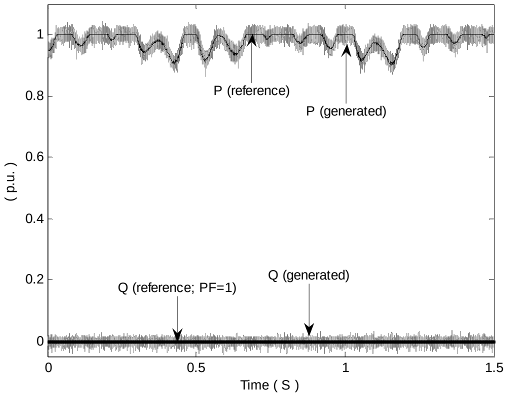

Fig. 17. Active and reactive power outputs in response to fluctuating wind speed

VI. REFERENCES

[1] J. F. Manwell, J. G. McGowan, and A. L. Rogers, *Wind energy explained*, John Wiley, 2002.

[2] T. Burton, D. Sharpe, D. Jenkins, and E. Bossanyi, *Wind energy handbook*, John Wiley, 2001.

[3] Permanent magnet synchronous generators for wind energy applications, [online] available: http://www.abb.com/motors&drives

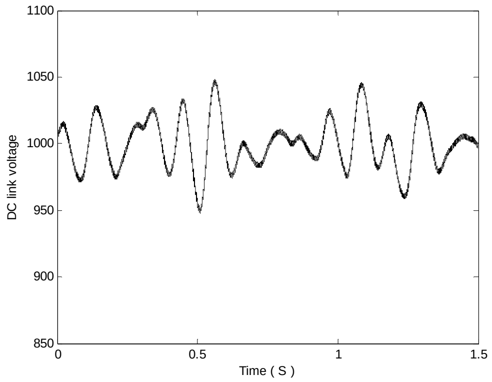

Fig. 18. DC link voltage variations in response to wind speed fluctuations

[4] S. Nomura, Y. Ohata, T. Hagita, H. Tsutsui, S. T. Iio, and R. Shimada, “Wind farms linked by SMES systems”, *IEEE Trans. on Applied Superconductivity*, Vol. 15, No. 2, pp. 1951-1954, June 2005.

[5] K. H. Sobrink, P. L. Sorensen, P. Christensen, N. Sondersen, K. Eriksson, and P. Holmberg, “DC feeder for connection of a wind farm”, presented at Cigre Symposium, Malaysia, Sep. 1999.

[6] M. R. Patel, *Wind and solar power systems*, CRC Press, 1999.

[7] S. K. Kim, E. S. Kim, J. Y. Yoon, and H. Y. Kim, “PSCAD/EMTDC based dynamic modeling and analysis of a variable speed wind turbine”, in *Proc. IEEE PES general meeting 2004*, Vol. 2, pp. 1735-1741.

[8] I. Schiemenz, and M. Steibler, “Control of a permanent magnet synchronous generator used in a variable speed wind energy system”, in *Proc. 2001 IEEE IEMDC*, pp. 872-877.

[9] M. Monfared, and H. Rastegar, “A flexible wind turbine model suitable for power system studies”, *14th Iranian Conference on Electrical Engineering (ICEE 2006)*, pp. 1-6.

[10] S. Ang, and A. Oliva, *Power-switching converters*, CRC Press, 2005.

[11] K. Tam, and P. Kumar, “Application of superconductive magnetic energy storage in an asynchronous link between power systems”, *IEEE Trans. on Energy Conversion*, Vol. 5, No. 3, pp. 436-444, Sep. 1990.

[12] M. Monfared, and H. Rastegar, “Dynamic active stall control of a grid connected wind turbine”, *21th International Power System Conference (IPSC 2006)*, pp. 2018-2026.