Laboratory Experiments on a Doubly Fed Induction Generator (DFIG) for Wind Turbine Application

Ben Ranayhossaini, Chris Rekiel, Joseph E. Warner, and George Kusic Phd.
University of Pittsburgh, bdr22@pitt.edu, cjr52@pitt.edu, jew53@pitt.edu, gkusic@pitt.edu

Abstract – Wind generator technologies have been, and are still being researched and explored to improve on the practicality of being a major energy supply in today's power domain. With grid connectivity being a large factor in present wind turbine installations, various technologies are being implemented to operate these systems with a wider range of operating speeds. A Doubly Fed Induction Generator (DFIG) system can generate power at constant frequency and a variable wind speed by controlling the rotor using a variable frequency drive (VFD). A VFD can force the generator into negative slip when sufficient wind is not available. Advantages of DFIG controlling the rotor side of an induction generator include control of the power-factor and the energy flow throughout the DFIG system. To gain peak efficiency in the generating system, scalar input is provided by a VFD to maintain a constant stator voltage output on a generator. An experiment was performed for a DFIG wind turbine configuration by injecting the rotor in an open-loop, self-excited environment, followed by experiment with a the closed-loop arrangement using an industrial grade Variable Frequency Drive (VFD) as the influence to the wound rotor of a DFIG.

Index Terms – DFIG, Induction Machine, VFD, Wind Turbine.

Introduction

Energy prices, supply uncertainties, and environmental concerns are driving the effort to rethink the global energy portfolio. Focus on renewable energy has sparked the effort in studying and researching ways to improve renewable energy technology to better support for large scale use[1]. Wind power technology being part of these efforts, has existed for some time; however, with continuous efforts, technological improvements can be made to make wind power generation a practical supply in today's power domain.

Wind turbines are commonly comprised of a drive train including the generator, shaft, and gearbox, three bladed rotors, and a tower. Capacity factors of wind turbines can vary between 30% and 40% over annual power generation because a wind turbine's output can vary depending on wind intensity and direction[1]. Because of the variability of wind, there is need to find a way to improve a wind turbine's grid stability; wind is a non-dispatchable resource therefore to accommodate a constant shaft speed, the system needs to be influenced. A classic way of converting and controlling mechanical torque is by means of a gearbox, where many current turbines use a three-stage gearbox placed between the main rotor shaft and the generator. The gearboxes task is to match the rotational speed of the rotor blades to the generator rotation speed; the gearbox always maintains a constant and an increasing speed ratio[2]. Recently, there has been an increase in implementation and study of the DFIG concept on wind turbine systems to also maintain a constant generator shaft speed.

A laboratory experiment was performed to better understand the theory, application, and practicality of a DFIG system on a wind turbine. The following lab equipment was used to simulate a wind turbine DFIG system and environment: Eaton-Cutler Hammer SVX9000 AF Variable Frequency Drive, Hampden Engineering Universal Laboratory Machine (ULM) Model 120 with stator windings wired to three poles, Hampden Engineering 2KVA Variable Capacitance Bank, Agilent 54622A 100MHz Oscilloscope, Westinghouse Style 291B710A1B AC Ammeter, Westinghouse Style 293B207A24 Wattmeter, Westinghouse Style 606B692A16 AC Voltmeter, R.S.R. 525 Multimeter, General Radio Co. Strobotac 631-B, GE 120V 40W Incandescent Bulb (Load). Ratings of this equipment can be found in Appendix A.

Introduction to Asynchronous Induction Machines

There are two different types of induction machines, cage rotor and wound rotor. The cage rotor, also known as Squirrel Cage, consists of a series of conducting bars laid into slots card in the face of the rotor and shorted at either end by large shorting rings. A wound rotor machine has a complete set of three-phase windings. These windings have leads brought out and tied to slip rings mounted onto the armature. This paper and simulation will concentrate on the wound rotor induction machine.

Assuming a three phase system on an induction motor, when voltage is applied to the stator coil windings, current flows through these coils and a magnetic field, $\mathbf{B}_s$, is propagated in the stator. This magnetic field then rotates within the stator. The rotational speed of the magnetic field is given by

$$n_{sync} = \frac{120f}{P} \qquad [1]$$

This is also known as the synchronous speed, where f is the system frequency in hertz, and P is the number of poles in the machine. This rotating magnetic field then passes over the rotor windings, inducing current, **I**. When this current flows through the windings, a force is induced on the rotor by the Lorentz Law

$$\vec{F} = \ell \vec{I} \times \vec{B} \qquad [2]$$

As the rotor approaches synchronous speed, the induced voltage on the rotor decreases. However, once the rotor is at synchronous speed there is no induced voltage, thus there is no current through the rotor to yield a magnetic field. With no rotor magnetic field, the induced torque becomes 0. If the speed of the machine is driven to a speed greater than n_{sync} the machine will behave as a generator because there is a reversal in direction of the torque. A typical torque/speed characteristic of an induction machine is shown in Figure 1.

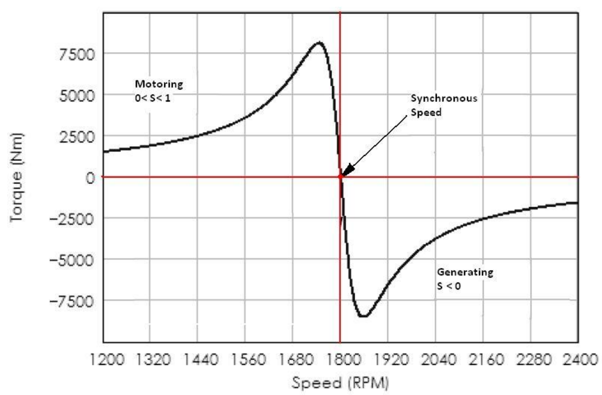

Figure 1: A typical torque/speed characteristic of an induction machine

The voltage induced in the rotor of an induction motor depends on difference in rotational speed between the stator field and the rotor field. This difference is used to define the slip speed of the machine. Slip speed is defined as

$$n_{slip} = n_{sync} - n_m \qquad [3]$$

where n_m is the mechanical shaft speed of the machine. With [3] the slip of the machine can be found by

$$s = \frac{n_{slip}}{n_{sync}} * 100\% \qquad [4]$$

Using the slip of the machine, the frequency on the rotor can be found using

$$f_r = sf \qquad [5]$$

In a wind turbine application, negative slip is desirable so the machine is in the generating region of its torque speed characteristic. To force the machine into the generating region, the rotor frequency may be influenced externally, therefore varying the slip.

DFIG Wind Turbine Model

A DFIG wind turbine makes use of a wound-rotor induction generator with external voltage on the rotor of the machine. In a Closed Loop scheme, the stator coils of the machine are connected to the grid. In an Open Loop scheme, or self-excited, the stator coils are connected to a capacitor bank to provide the reactive energy needed to propagate the rotating magnetic field. The external voltage in this experiment is being applied by a Variable Frequency Drive (VFD). Figures 2 and 3 are schematic representations of these two schemes.

The purpose of the VFD in the DFIG is to manipulate the frequency of the rotor voltage to keep the machine in the generating region. The commercial VFD operates only with the following fixed, steady-state settings: output frequency, output voltage, and output power factor.

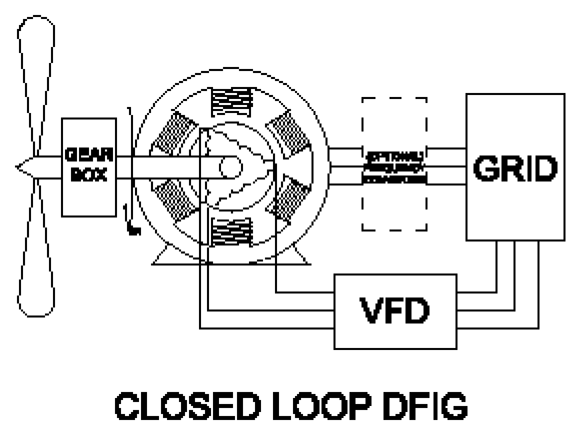

Figure 2: Closed Loop DFIG configuration with external voltage applied by VFD

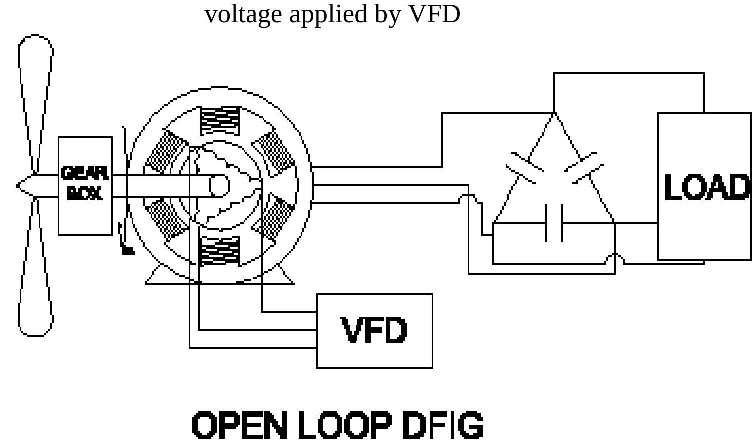

Figure 3: Open Loop DFIG configuration with external voltage applied by VFD

In the open loop configuration, capacitors are connected to the stator of the machine to provide sufficient excitation reactance to produce voltage at the stator terminals. Factors that affect the regulation of the generated voltage are the machine magnetization properties, magnitude of the excitation capacitance, and the machine's resistive circuits. If the excitation capacitance is too small, the generator will fail to building up voltage. If it is too large, the machine may experience voltages higher than its nameplate rating[5].

A disadvantage of a self-excited DFIG configuration is that with properly sized capacitors attached to the stator, the generated voltage decreases with an increasing, balanced, three phase load, neglecting the power factor[5].

In a closed loop configuration, the reactive energy required to stabilize the magnetic field is provided by the grid/frequency converter.

Laboratory Experiments

With an external, variable frequency source exciting the wound rotor of the induction machine, the equivalent circuit of the machine is shown in Figure 4.

When the stator is connected to the grid, the grid imposes its voltage and frequency to the stator of the machine, therefore the rotor current from the VFD is a moderator of active and reactive power between the induction machine and the grid. In a self-excited DFIG arrangement, it is required that the voltage be controlled to maintain the nameplate ratings of the machine.

E_r is a control voltage in the self-excited DFIG arrangement. Under system load

$$E_s = i_s jX_s + i_s Rs + i_s Z_{load} \qquad [8]$$

Because the DFIG's mmf's rotational direction can be in the same or the opposite direction, the frequency of the stator for a 3 pole machine is

$$f_s = f_m \pm f_r \qquad [9]$$

where f_m is the mechanical shaft frequency. To demonstrate a DFIG in the self-excited environment, data was acquired by holding the shaft speed constant at 3540 rpm and varying the frequency of the injected voltage on the rotor.

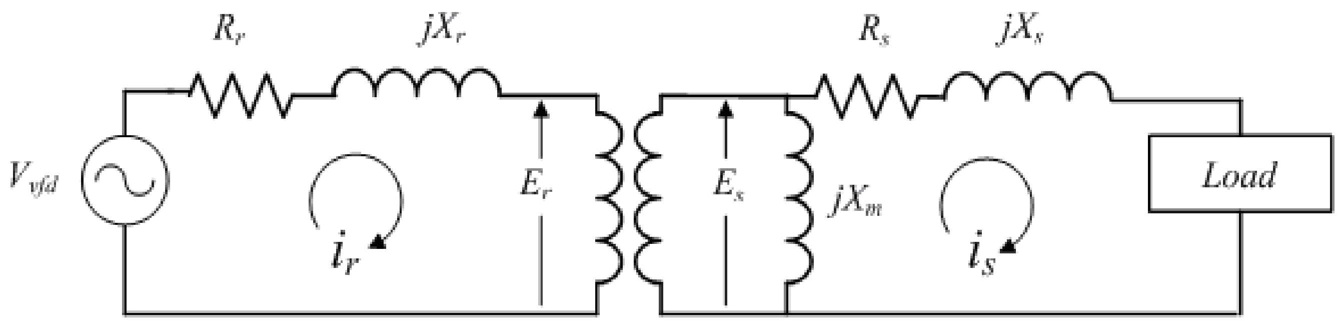

Figure 4: The equivalent circuit of the DFIG with an external voltage supplied by the VFD, with load

The induction machine stator and rotor voltages are given by the following steady-state phasor equations

$$E_r = V_{vfd} - i_r R_r - i_r jX_r \qquad [6]$$

$$E_s = i_s jX_s - i_s R_s \qquad [7]$$

The as part of the equivalent circuit, the following machine parameters were measured:

$Rr = 1.2\Omega$, $Xr = .844\Omega$, $Rs = .4\Omega$, $Xs = .152\Omega$,

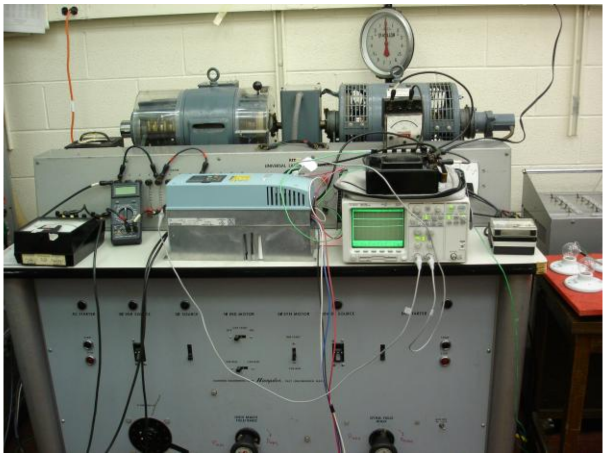

Figure 5: The laboratory experimental equipment

A wye-configuration of 30 µF capacitors was connected to the terminals of the stator.

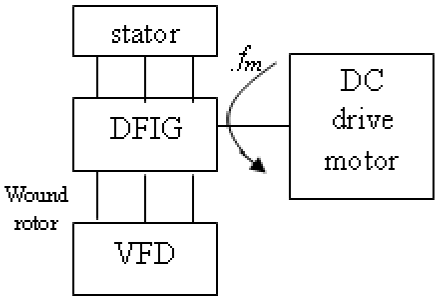

Figure 6: Laboratory experimental setup

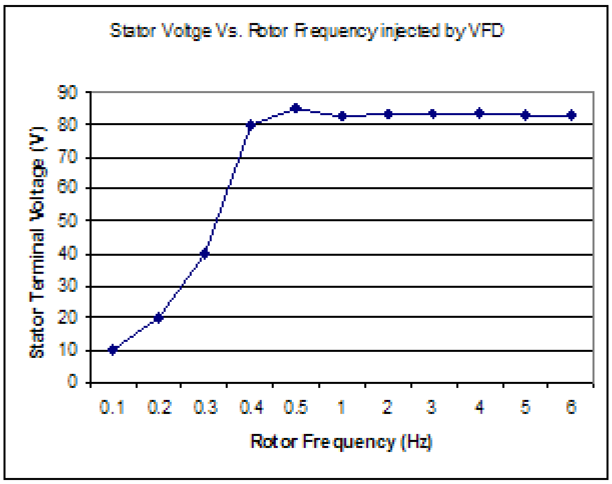

Figure 7: Experimental results of the stator line to line voltage against the VFD frequency injected into the rotor. The machine speed and capacitance are held constant

Figure 7 shows a plot of the stator terminal voltage against the injected rotor frequency, where the frequency injected by the VFD was varied. The capacitance was held at 30 µF with the dynamometer speed varied. It was calculated that the resonant capacitance of the machine used in the lab experiment at 3600 rpm is 31.4 µF. Capacitance was then varied when the shaft speed was held constant. The data taken is seen in Figure 8.

In the open loop system, the electric energy supplied by the system can work under its nominal conditions, and the voltage magnitude and frequency may be maintained within the tolerated limits of the system. Capacitors must be connected to the stator of the machine to serve as a source for the reactive energy that is required to generate the magnetic field of the machine. With variable capacitance it is possible to maintain a constant stator voltage in variable wind with a VFD. However, the system is sensitive to the load; and can become unstable. Investigation of a loaded system is to be investigated.

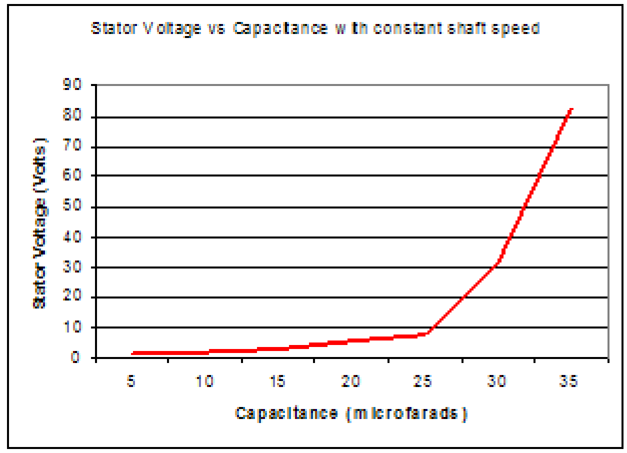

Figure 8: Stator voltage with a varied capacitance at a constant shaft speed.

The next experiments are a closed loop DFIG with a grid connection. The initial step in this simulation is to synchronize the machine to the grid, once the machine is up to its operating speed. Because of stator voltage limits, the equivalent grid power was dropped to 85 VAC 60Hz for the experiment. Figure 9 is a schematic showing the connection, with 120V 40W light bulbs in series. These are used to limit currents as the stator is synchronized to the grid. When the machine is not synchronized with the grid, there is a voltage drop across the bulbs because the output of the machine's stator is not in phase with the grid power. Depending on the vector phase difference between the two, the lights flicker at the difference frequency. When the machine is fully synchronized with the grid, the bulbs will go completely out; effectively the terminal voltage on the machine matches that of the grid, resulting in no potential difference across the bulbs. Once this occurs, the switch may be thrown, shorting out the bulbs and matching the stator with the grid. This action simulates a synchroscope for generators.

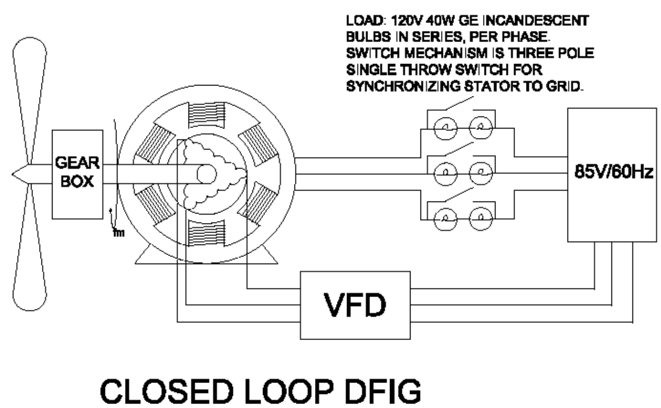

Figure 9: Closed loop simulation, synchronizing the machine to the grid

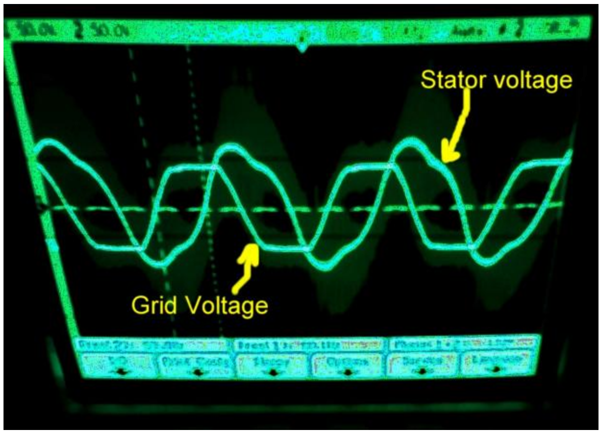

Figure 10: An oscilloscope probe of the Stator voltage and grid voltage before synchronizing. Once these waveforms are matched (in phase), the switch may be thrown

Once synchronized with the VFD activated, steady-state readings were sampled from attached meters. Figure 11 is a plot of the stator voltage as a function of machine speed, with $f_m + f_{vfd} = 60$ Hz. The stator voltage remained steady as the Shaft speed varied.

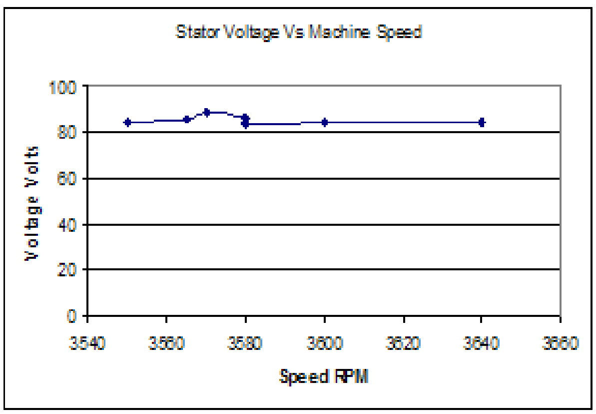

Figure 11: The Stator voltage vs Machine Speed
$f_m + f_{vfd} = 60$ Hz

Figure 11 shows the stator voltage vs. machine speed. Note that the stator voltage remains nearly constant over the varying speed of the rotor. This is important in verifying negligible stator voltage oscillations over the rotor speeds as it synchronizes with the frequency of the grid. Observe that the machine speed in the graph centers on the nominal speed of 3600 rpm. 3600 rpm is the shaft speed of the machine during exact synchronization with the grid. Equation [1] illustrates this relationship. Figure 12, shows that the stator voltage remains relatively constant as the real power is changed on the VFD by adjusting the power factor. Figure 13 shows a similar plot of the VFD power supplied to the rotor against the stator power, with the power factor varied. Figure 14 shows a plot of the stator voltage against reactive power on the machine's stator and Figure 15 shows a plot of the stator voltage as a function of power factor and Figure 16 is a plot of the stator voltage against the rotor frequency. Note the Stator Voltage scaling for the plots in Figure 14 and Figure 16.

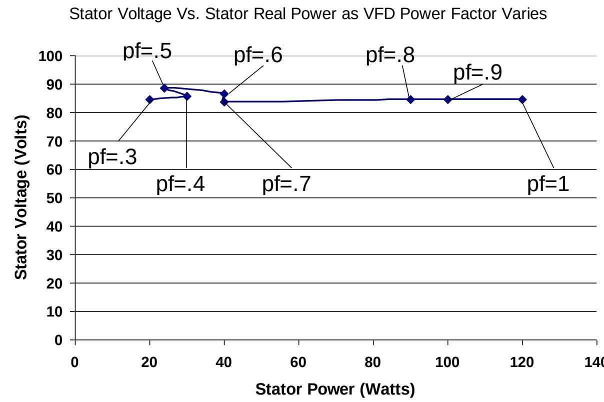

Figure 12: The Stator voltage vs Stator Real Power delivered to the 'Grid'. Machine speed is kept constant at 3600 RPM, the critical point on the torque speed characteristic, within a reasonable tolerance. Power factor of the VFD is marked for each point.

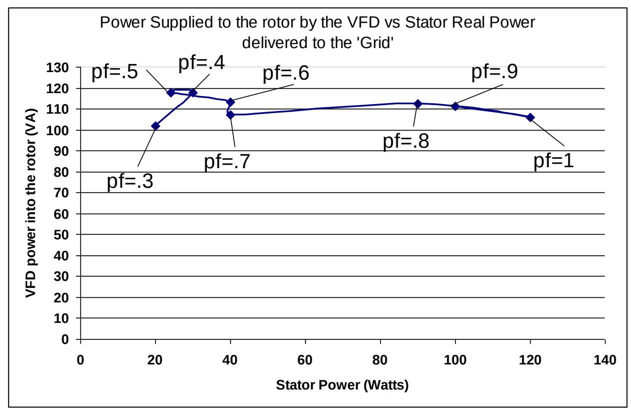

Figure 13: Power Supplied to the rotor by the VFD vs Stator Real Power delivered to the 'Grid'. Machine speed is kept constant at 3600 RPM, the critical point on the torque speed characteristic, within a reasonable tolerance. Power factor of the VFD is marked for each point.

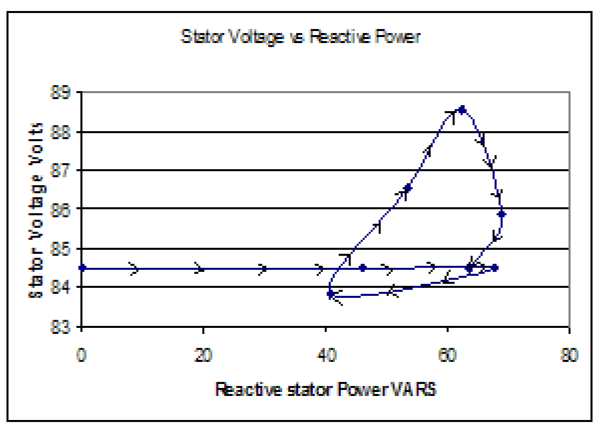

Figure 14: The Stator voltage vs Stator Reactive Power Delivered to the 'Grid'

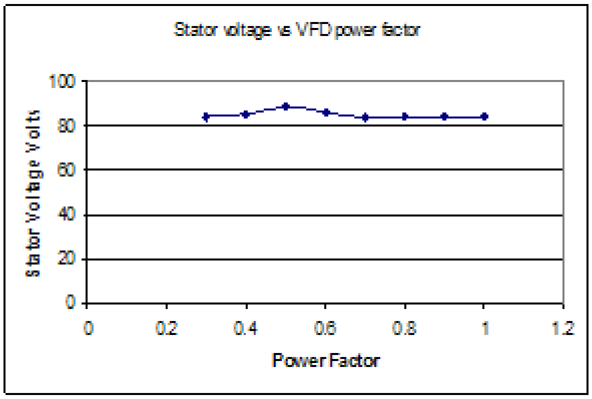

Figure 15: The Stator voltage vs VFD Power Factor

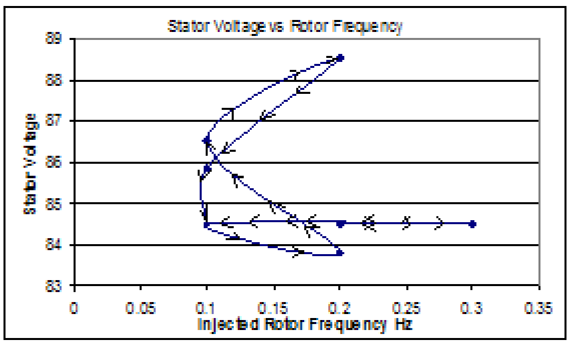

Figure 16: Sampled Stator Voltage vs Sampled VFD rotor frequency

Analysis

Successively, we can show that the stator voltage can be maintained by injecting the rotor circuit with a VFD output. Note that increasing the rotor speed produces transients in the voltage of the stator. We can also say that by varying the power factor, which effectively changes the magnitude of the real and reactive power components, we can still maintain a constant stator voltage; however, the stator current will compensate accordingly.

By inspecting Figure 13 it is apparent that the net power into the DFIG is negative for stator output of less than 110W. Once the stator output exceeds 110 watts the power applied to the rotor by the VFD is less than the output power, and a net positive power is delivered to the grid. In other words, the system will not deliver power to the grid until input power from the wind turbine exceeds 110W.

Conclusion

The simulation results from the proposed models show the capabilities of the DFIG operating in a closed loop and open loop environment. The DFIG was initially simulated by injecting the rotor in an open-loop, self-excited environment, followed by simulation in the closed loop arrangement. This lab simulation suggests an aspect of regulation of rotor parameters to control stator output on a DFIG. The DFIG may be fed and controlled from the rotor with a VFD, in both self-excited and grid connected environments. To gain peak efficiency in the generating system, the scalar input provided by the VFD adapted the rotor characteristics in such a way that voltage was maintained on the generating end. The simulation suggests interesting and attractive performances of the DFIG in an experimental environment.

Acknowledgment

Special thanks to Dr. George Kusic for his mentoring, advice, and contribution to the lab simulation.

Reference

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Appendix A

Eaton VFD SVX9000 AF drive parameters- V1-3~208-240V 50/60Hz I1- 31A, Output V2 3~0-V1 0-320Hz, I2 25/31A, P2 7.5CT/10VT

Hampden ULM Model 120 parameters- Universal Machine: 1.5-2 KVA, 208/120V 3 phase 60 Hz. 3400-3600 RPM in AC modes. Stator, 24 slots wound with 12 coil single layer winding, coil pitch 1-12. Measured circuit per phase equivalents: Rs=.4 Ohms, Ls=14.07 mH, Rr=1.0 Ohms, Lr=2.55mH.