Real-Time Wind Turbine Emulator Suitable for Power Quality and Dynamic Control Studies

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***Abstract*— Wind turbines are increasingly becoming significant components of power systems. To evaluate competing wind energy conversion technologies, a real-time Wind Turbine Emulator, which emulates the dynamic torque produced by an actual turbine has been developed. This is necessary since the real world performance of a wind turbine, subjected to variable wind conditions is more difficult to evaluate than a standard turbine generator system operating in near steady state. This emulator is capable of reproducing both the static and dynamic torque of an actual wind turbine. It models the torque oscillations caused by wind shear, tower shadow, and the obvious pulsations caused by variable wind speed. Also included are the dynamic effects of a large turbine inertia. This emulator will allow testing without the costly construction of the actual turbine blades and tower to determine the strengths and weaknesses of competing energy conversion and control technologies.**

***Index Terms*— Wind Turbine Emulator, Wind Turbine Simulator, Wind Shear, Tower Shadow, Torque Oscillations, Wind Turbine**

I. Introduction

Torque and power generated by a wind turbine is much more variable than that produced by more conventional generators. In three bladed horizontal axis wind turbines, the most common [1] and largest [2] periodic power pulsations occur at what is known as a 3p frequency. This is 3 times the rotor frequency, or the same frequency at which the blades pass by the tower. The sources of these power fluctuations are due both to stochastic processes that determine wind speed at different times and heights, and to periodic processes. These periodic processes are due largely to two effects termed wind shear and tower shadow. Wind shear is used to describe the variation of wind speed with height while tower shadow describes the redirection of wind due to the tower structure. Thus, even for a constant wind speed at a particular height, a turbine blade would encounter variable wind as it rotates. Torque pulsations and therefore power pulsations are seen due to the periodic variations of wind speed experienced at different locations. These torque oscillations are important to model since they can have wide ranging effects on control systems and power quality. A wind turbine emulator or simulator would be a useful tool to determine the effects of these variable power fluctuations without costly actual turbine construction.

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There have been several turbine simulators that have been created to emulate the wind turbine shaft. These have had various designs and applications for which they were appropriate. The simplest and most common approach is to use a basic steady state torque equation to calculate wind torque and use this to determine the acceleration on the turbine inertia [3]-[5]. However, simulators have limits on what they are capable of emulating, based on the models used to construct them. For instance, some simulators are capable of dynamic simulations [6] while others are only capable of performing steady state simulations [3]. The simulator still may only emulate the elements incorporated into the model. The emulator/simulator outlined in this paper includes several important components of which one or more was missing in other simulators. These components are: a variable wind speed, turbine inertia and a wind shear and tower shadow model.

The majority of previous simulators included the effects of the turbine inertia [3]-[8], which indicates how important it is, although the consequence of neglecting it were not demonstrated.

None of the lab simulators reviewed [3]-[8] included wind shear or tower shadow effects. This makes these simulators unsuitable for studying any issues that may arise due to the 3p power pulsations resulting from these effects. These effects have not been included in reviewed lab simulators although they have been included in off-line simulation studies [9],[10].

Different types of machines have been used to emulate the turbine shaft. Both the induction machine [3],[11],[12] and DC machines [4]-[8],[13] have been used in wind turbine simulators. However a PMSM (permanent magnet synchronous machine) would be ideal in terms of power density, inertia, impulse torque and speed response [14]. PMSM have an impulse torque two orders of magnitude larger than that of a DC servomotor and have greater power density than DC machines and even induction machines [14]. Therefore, for the emulator constructed, a PMSM is used to produce a torque that models wind turbine torque and compensates for the lower inertia of the stiffly connected drive machine. A PC implementing RT-Linux determines the required emulation turbine torque using wind speed data and measured turbine angular speed and angular position. The shaft position, speed, and shaft torque are measured to determine what compensation is required to emulate the driving torque of the wind turbine and inertial dynamics. Different wind series may be used to determine how a turbine would react under different environmental conditions. The wind speed data can be obtained either from a wind speed model or an actual wind time series taken in the field from an anemometer. In this study the wind turbine emulator is evaluated by connecting the turbine shaft to a grid connected induction generator. The emulator is fed with an actual measured wind time series. In the future, this WTE (Wind Turbine Emulator) could be used to study the strengths and weaknesses of a variety of combinations of generator, converter and control system configurations.

II. Emulator Construction

The emulator is based on the field system shown in Fig. 1, where the turbine generator is directly connected to the grid. An ideal gearbox (not shown) connects the turbine rotor to the generator. The lab system is realized by replacing the wind, gearbox and turbine rotor with a PC, voltage source converter (VSC) and PMSM as shown in Fig. 2. The PC implementing RT-Linux uses a wind shear/tower shadow model, an inertial model and a variable wind to control the PMSM to emulate the driving torque of a wind turbine. These models will be briefly outlined as will the computer hardware components along with the drive components and control methodology used.

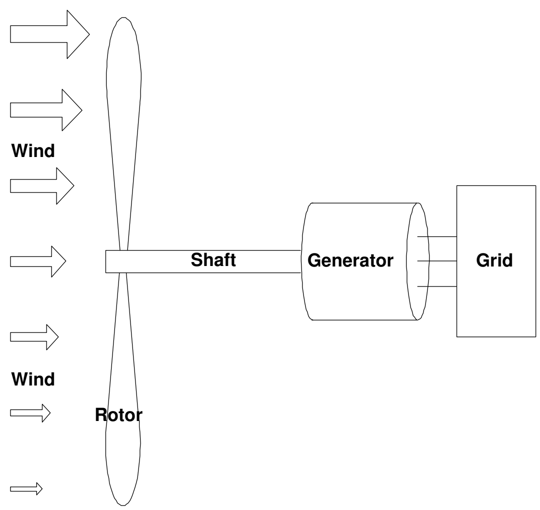

Fig. 1. Field System: Simplified Diagram of Modelled Wind Turbine System

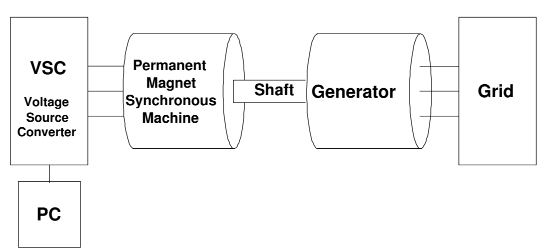

Fig. 2. Lab System: Simplified Diagram of Wind Turbine Emulator - The lab system is realized by replacing the wind and rotor of the field system with a PC, VSC and PMSM

A. Tower Shadow/Wind Shear Model

As a turbine blade rotates, it is acted upon by wind at various heights. The variation of wind speed with height is termed wind shear. Wind speed generally increases with height. Torque pulsations, and therefore power pulsations, are observed due to the periodic variations of wind speed experienced at different heights. Power and torque oscillate due to the different wind speeds encountered by each blade as it rotates through a complete cycle [15],[16]. For instance, a blade pointing upwards would encounter wind speeds greater than a blade pointing downwards. During each rotation the torque oscillates three times because of each blade passing through minimum and maximum wind.

The distribution of wind is also altered by the presence of the tower. The effect depends on whether the rotor is located upwind or downwind of the tower. For upwind rotors, the wind directly in front of the tower is redirected and thereby reduces the torque at each blade when in front of the tower [10]. For downwind rotors the wind is blocked by the tower and again reduces the torque at each blade when behind the tower. This effect is called tower shadow. The torque pulsations due to tower shadow are most significant when a turbine has blades downwind of the tower and the wind is blocked as opposed to redirected [16]. It has been reported that the tower shadow in downwind rotors can cause up to a 10% peak-peak torque fluctuation whereas the effect on upwind rotors is less severe [17]. For this reason, the majority of modern wind turbines have upwind rotors. The model used in this paper will therefore only deal with the tower shadow torque oscillations in three bladed upwind rotors.

To determine control structures and possible power quality issues, the dynamic torque generated by the blades of a wind turbine must be represented. It is therefore important to model these wind shear and tower shadow induced 3p torque pulsations for a meaningful wind turbine emulator.

The constructed WTE relies on the analytical formulation of the generated aerodynamic torque of a three bladed wind turbine, including effects of wind shear and tower shadow presented in [18]. The formulation combines and builds upon previous work to create/develop a pragmatic model appropriate for use in a wind turbine emulator. Tower shadow equations come mainly from [9], while wind shear equations are adapted from [1] and [19]. Torque is normalized to steady state torque at average spatial wind speed to yield (1). The normalized torque formulation is completely described in [18] and only the final result is used and presented in this paper as (1)-(3),

$$\overline{T_{ae}(t,\theta)} = 1 + \frac{2}{mV_H}[v_{eq_{ws}} + v_{eq_{ts}} + (1-m)V_H] \quad (1)$$

$$v_{eq_{ts}} = \frac{mV_H}{3R^2}\sum_{b=1}^{3}\left[\frac{a^2}{\sin^2\theta_b} ln\left(\frac{R^2\sin^2\theta_b}{x^2}+1\right) - \frac{2a^2R^2}{R^2\sin^2\theta_b + x^2}\right] \quad (2)$$

$$v_{eq_{ws}} = V_H\left[\frac{\alpha(\alpha-1)}{8}\frac{R^2}{H^2} + \frac{\alpha(\alpha-1)(\alpha-2)}{60}\frac{R^3}{H^3}\cos 3\theta_1\right] \quad (3)$$

where $v_{eq_{ws}}$ = component of equivalent wind speed caused by the wind shear, $v_{eq_{ts}}$ = component of equivalent wind speed caused by the tower shadow, V_H = wind speed at hub height, $m = [1 + \frac{\alpha(\alpha-1)(R^2)}{8H^2}]$, R = radius of the rotor disk, H =

elevation of rotor hub, a = tower radius, x = longitudinal distance from blade to tower center, θ_b = azimuthal angle of blade b, and α = empirical wind shear exponent.

This formulation includes turbine specific parameters such as radius, height and tower dimensions (as shown in Fig. 3), as well as the site specific parameter α, the wind shear exponent. This allows versatility in the emulator as the model can be applied to a wide variety of wind turbines.

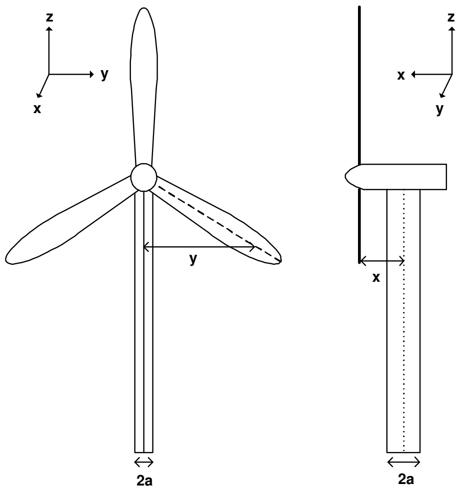

Fig. 3. Dimensions used in tower shadow formula

It is shown in [18] that the tower shadow effect is more dominant than the wind shear effect in determining the dynamic torque. It is also established that as expected, the tower shadow effect is more pronounced when the blades are closer to the tower.

B. Inertia Model

The inertia model is determined by equating the generator acceleration in the field and lab systems. The effect is to alter the turbine torque that the PMSM will produce in response to a given wind, such that the effect of the larger turbine rotor inertia is emulated. A mechanical diagram of both the field system and the representative lab system is shown in Fig. 4, where T_{PM} = PMSM torque, T_{wind} = aerodynamic turbine rotor torque, T_G = generator torque, J_{PM} = PMSM inertia, J_G = generator inertia, and J_H = turbine rotor inertia. Equations of motion may be written for both systems and solved to determine the reference torque (4) required for the PMSM, where $T_{wind_H} = \frac{T_{wind}}{n}$ and $J_H = \frac{J_H}{n^2}$.

$$T_{PM} = \left(\frac{J_{PM} + J_G}{J_{H_H} + J_G}\right) T_{wind_H} + \left(\frac{J_{H_H} - J_{PM}}{J_{H_H} + J_G}\right) T_G \quad (4)$$

However, in this setup the generator torque is not directly available and it must be determined from the shaft torque (T_{Shaft}) and PMSM torque. The generator torque can be determined from (5) which allows (4) to be expressed in the final form of (6) for use in the WTE.

$$T_{Shaft} = \left(\frac{J_G}{J_{PM} + J_G}\right) T_{PM} + \left(\frac{J_{PM}}{J_{PM} + J_G}\right) T_G \quad (5)$$

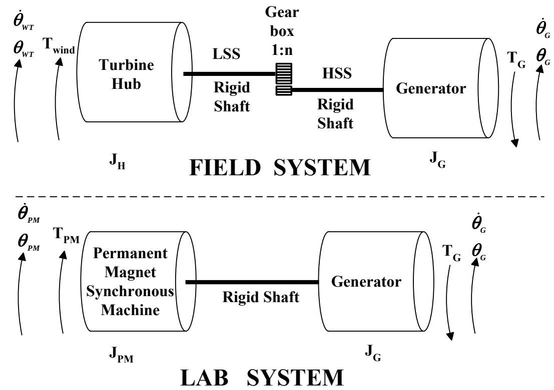

Fig. 4. Mechanical diagram of field system (with rigid LSS and rigid HSS) and lab system

$$T_{PM} = \left(\frac{J_{PM}}{J_{H_H}}\right) T_{wind_H} + \left(\frac{J_{H_H} - J_{PM}}{J_{H_H}}\right) T_{Shaft} \quad (6)$$

Therefore the wind turbine emulator will accurately represent the field wind turbine system if the driving torque T_{PM} is controlled according to (6).

C. Hardware Components and Control

The detailed WTE experimental setup is shown in Fig. 5. The PC used in the WTE is a PIII 1GHz processor running RT-Linux. PMSM position and speed are calculated by an Altera Flex10K70 based FPGA board based on input from a 4000 slot optical encoder. Additional signals from voltage and current sensors are processed using a 8kHz A/D board. The PMSM is controlled by the PC through a 3-phase VSC (voltage source converter). Required gating signals are processed by the FPGA and routed out to the VSC. The VSC therefore provides the PMSM with voltage, and thus current, of variable frequency, amplitude and phase.

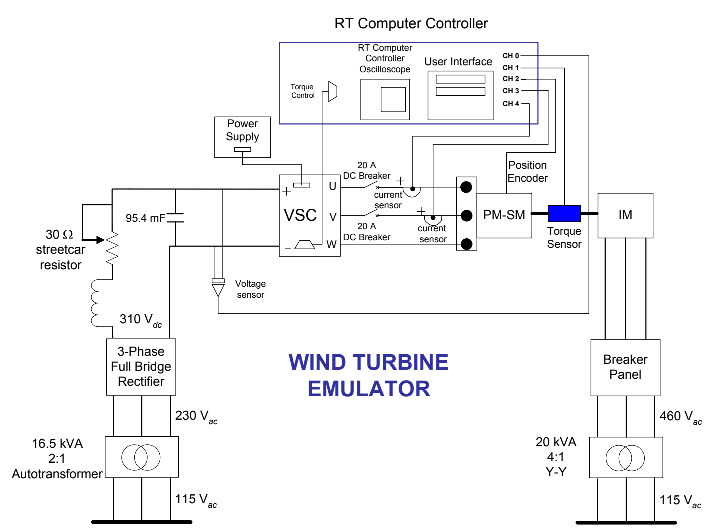

Fig. 5. Wind Turbine Emulator: Experimental Setup

The PMSM is configured as a dq-frame torque controlled PMSM, with a control bandwidth of approximately 130 Hz. This allows sufficient speed to model the frequencies of interest in wind turbines. These frequencies that result from wind variation, tower shadow, wind shear and shaft dynamics are generally less than 15 Hz. The PMSM torque reference is calculated as per (6).

III. RESULTS

The following results are based on a 180kW fixed speed 3-bladed wind turbine. The specifications for this field turbine are presented in Table 1 of the Appendix. The average torque of the WTE was scaled down by a factor of 26 from the average field torque seen under the wind conditions used in the experimental setup.

The wind speed data used in all experiments was a 60 second portion of a 10 minute time series. This block of data was placed in a loop such that the WTE could run indefinitely. The presented portion of this data corresponds to the period from 25 - 30 seconds in this data set. This section was chosen as it contained considerable variation in the wind speeds that served to demonstrate the functioning of the WTE. The 60 second portion of the wind series data had an average wind speed of 7.27 m/s, with a minimum of 6.35 m/s and a maximum wind speed of 8.58 m/s.

The turbine torque oscillations due to tower shadow and wind shear were calculated based on the turbine specifications and yielded approximately a 6% peak to peak oscillation. These oscillations were sufficient to cause a resultant fluctuation in the output current, however when a variable wind is introduced the effects are not as obvious without detailed spectrum analysis. Therefore, for the purpose of a clear presentation, these oscillations were amplified to a level of 30% peak to peak, such that the effects due to tower shadow and variable wind could easily be distinguished in the time domain.

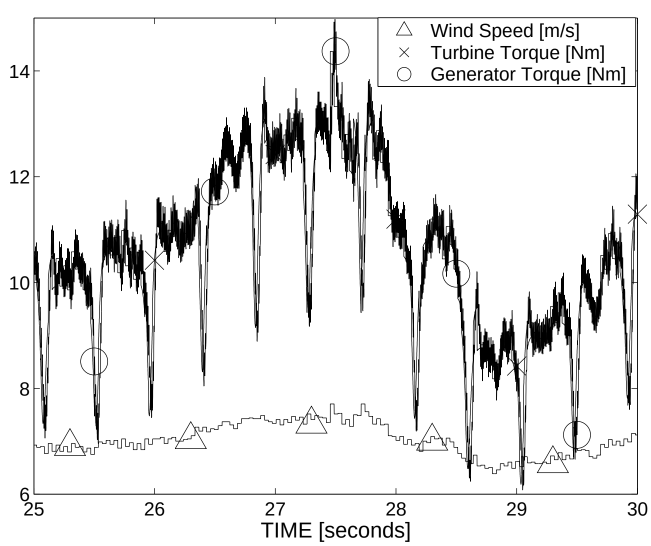

Fig. 6. Generator Torque including only effects of Tower Shadow and Wind Shear

The emulator was run with variable wind speed including only the effects of tower shadow and wind shear with the inertia of the turbine being represented by the inertia of the PMSM. The ratio of PMSM inertia to generator inertia is approximately two. This nearly eliminates the effect of a large rotor inertia that would be seen in real systems.

As shown in Fig. 6, the variable wind speed causes random fluctuations in the turbine torque whereas the tower shadow effect causes regular torque depressions at a frequency of 2.1 Hz (3 times the rotor frequency). The generator torque closely follows the turbine torque as there is no significant inertia to buffer the oscillations. The effects of both the variable wind and tower shadow can be clearly seen in Fig. 7. The instantaneous line current varies in relation to the changing wind with a noticeable depression at a frequency of 2.1 Hz.

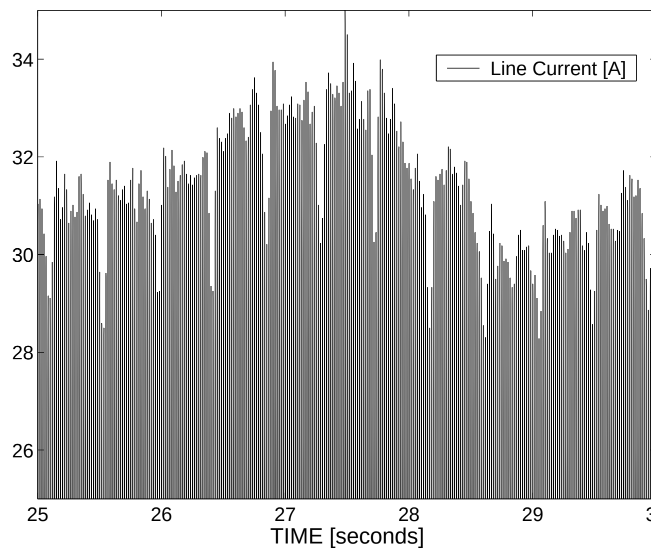

Fig. 7. Line current from generator showing depressions due to Tower shadow effect and variations due to changing wind speeds

For frequency domain presentation, the realistic 6% torque oscillations are used. The mean-square spectrum of the generator torque when the WTE is imitating conditions from tower shadow and variable wind is shown in Fig. 8. Spikes are clearly seen at the 3p frequency (2.1Hz) and multiples of the 3p frequency, although many other frequencies are also present. These can be explained by looking at the frequency spectrum of the wind series, where it can be determined that much of the spectrum below 2Hz, and the peaks near 5Hz and 16Hz are due to this particular wind series. It is seen that the tower shadow/wind shear model introduces many frequencies into the aerodynamic torque that could be important in power quality or turbine control.

The emulator was again run with variable wind speed but this time including the effects of tower shadow and wind shear with the inertia of the turbine rotor being accurately represented. The ratio of turbine inertia to generator inertia used was 23:1 as determined by the ratio of the modelled wind turbine. As done previously, the 6% tower shadow induced oscillation will be used when displaying frequency spectrum, while 30% will be used for time domain presentation.

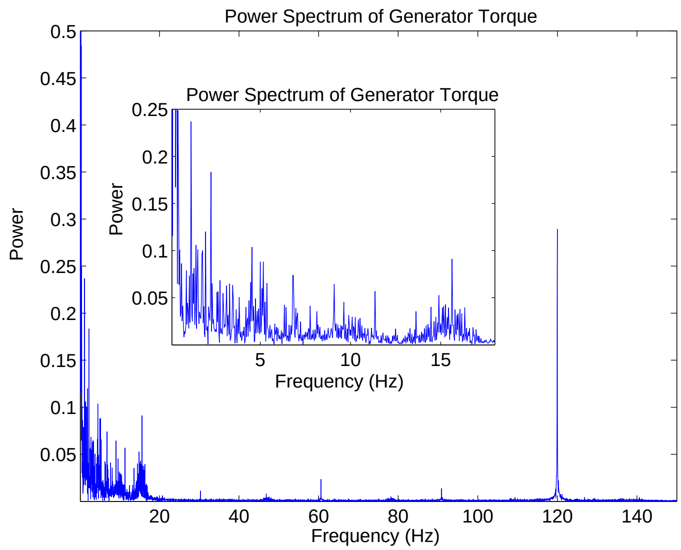

Fig. 8. Frequency spectrum of the generator torque for 6% tower shadow induced torque oscillation without inertial effects

The effects of a large turbine rotor inertia can be clearly seen by comparison of Fig. 6 to Fig. 9. The average turbine torque is unchanged but the generator torque fluctuations caused by changing wind conditions are reduced, as is the generator torque depression due to tower shadow. The energy reduction due to the tower shadow is spread over a larger time period resulting in a smoothing of generator torque. The result of this can also be observed in Fig. 10 where although the depressions can still be clearly seen at a frequency of 2.1 Hz, they are significantly reduced in amplitude and increased in width as compared to the depressions shown in Fig. 7. Both the torque and instantaneous line current also show considerable smoothing of the effects due to the variable wind.

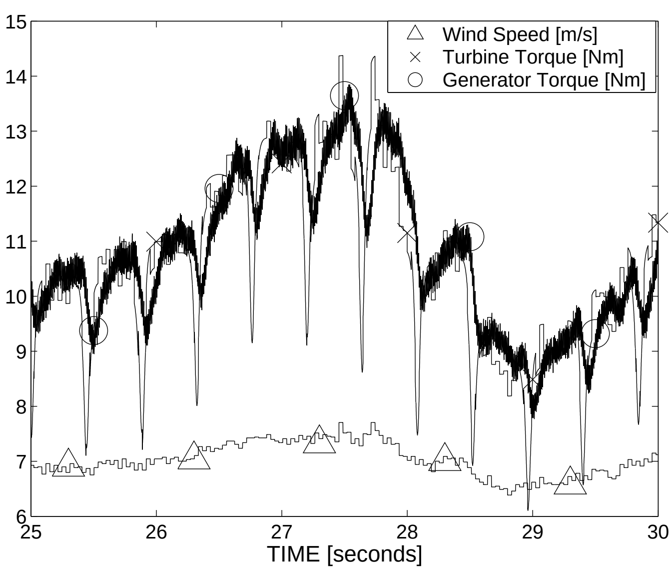

Fig. 9. Generator Torque including effects of Tower Shadow, Wind Shear and inertia 23 times larger than generator

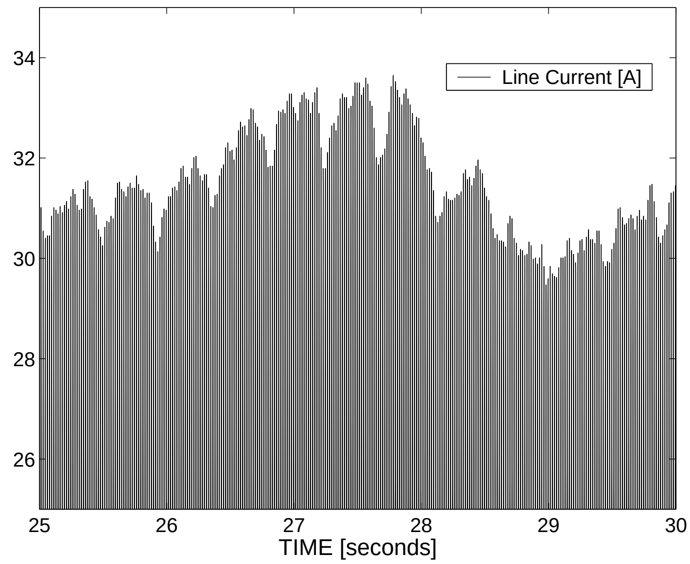

Fig. 10. Line current from generator showing depressions due to Tower shadow effect and variations due to changing wind speeds smoothed by large turbine inertia

Comparing the frequency spectrum of the generator torque using the emulated inertia (Fig. 11) and without emulated inertia (Fig. 8) clearly shows how the large inertia acts as a low pass filter. Higher frequency components are almost eliminated, while the lower frequencies are significantly attenuated.

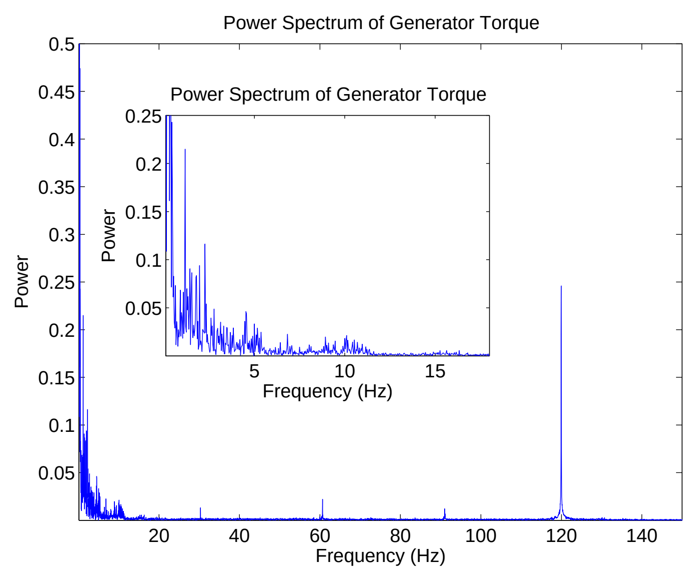

Fig. 11. Frequency spectrum of the generator torque for 6% tower shadow induced torque oscillation with inertial effects included

IV. Conclusions

A real-time Wind Turbine Emulator (WTE) was constructed that is capable of reproducing the dynamic torque that would be produced by a modelled wind turbine under specific wind conditions. The WTE was shown to successfully model the effect of tower shadow and large turbine rotor inertia.

The tower shadow effect was shown to cause a predictable torque depression in turbine torque that was transferred to the generator and seen in output line currents. The transmission of this torque fluctuation was shown to be less severe in cases where a larger turbine rotor inertia was included in the emulation. The effect of variable wind and the torque and output current fluctuations produced were also shown to be smoothed by a large turbine rotor inertia. These effects were confirmed by both time domain and frequency domain analysis. In the future, an improved emulator should attempt to include unmodelled effects such as shaft and blade dynamics for increased utility.

The WTE is capable of emulating and therefore evaluating various turbines under a wide variety of wind conditions. These wind conditions could be actual measured site conditions or developed from wind models anticipating conditions that a wind turbine would experience. The WTE has the advantage that the same wind conditions could be reproduced for different turbines under different control regimes. The WTE could determine the torque oscillations expected under these conditions and allow for evaluation of suitability for placement at a given site.

V. Appendix

Parameters	
Rated Power	180 kW
Number of blades	three
Rotor Diameter	23.2 m
Hub Height	30 m
Rotor speed	42 rpm
Rotor inertia J_{H_H}	$102.8 kgm^2$
Generator Inertia J_G	4.5 kgm^2
Ratio of Rotor to Generator inertia	23
Tower Diameter	1.7 m
Distance from blade to tower center	2.9 m
Wind shear exponent (α)	0.3

TABLE I
Wind Turbine Specifications

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