Development of Wind Turbine Simulators Using PSCAD

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***Abstract*—In this paper, a wind turbine simulator is developed using PSCAD. The wind turbine static characteristics are modeled using the relation among the turbine power, the wind speed, and the blade pitch angle. Also, the dynamic characteristics of the wind turbine are modeled through a two-mass oscillating system, representing the turbine and the generator connected by elastic shaft. The system considered is designed to show the effects of the tower shadow effect and blades asymmetry. Torsional oscillation effect on the drive train is also considered. A pitch angle controller is used to limit the turbine output power to the rated value to protect the coupled generator. Simulation results are presented to verify the wind turbine simulator performance.**

***Index Terms*—Wind energy, turbine simulator, two-mass model, tower shadow, pitch angle control, torsional vibration.**

I. INTRODUCTION

A WIND electrical generation system is the most cost competitive of all the environmentally clean and safe renewable energy sources in the world. It is also competitive with fossil fuel generated power. Although the history of wind power goes back more than two centuries, its potential to generate electrical power began to get attention from the beginning of the last century. However, during the last three decades, wind power has been seriously considered to supplement the power generation by fossil fuel method. In recent years, wind power is gaining more acceptances because of environmental and safety problems of conventional power plants and advancement of wind electric generation technology.

The world has enormous resources of wind power. It has been estimated that even if 10% of raw wind potential could be put to use, all the electricity needs of the world would be met [1]. The major components of the wind turbine generation system consist of the high inertia turbine and the low inertia generator coupled with elastic shaft. Gearbox is usually used to turn the slow rotation of the blades into a quicker rotation that is more suitable for generating electricity. The wind speed variations, gusts and turbulences have influence on the turbine output power. The wind speed pattern is distributed unequally over the wind turbine blades as the wind velocity is higher at higher altitude. As a result, torque fluctuations with low frequency can be realized, and these fluctuations are proportional to the turbine speed. 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 and largest periodic power pulsations occur at what is known as a 3p frequency [3].

This is three 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 simulator would be a useful tool to determine the effects of these variable power fluctuations without costly actual turbine construction [3], [4]. Using the pitch angle control is important to protect the MW turbines from excessive wind shear force which may cause the blade fatigue at high wind speed. The wind turbine generation systems usually run at a wind speed from 5[m/s] up to 25[m/s] and the rated power can be extracted at a wind speed equal to about 12-16[m/s] [2].

To evaluate the potential of any electrical generator scheme and to improve the overall, it is desirable to have access to a drive facility that can simulate the characteristics of renewable energy converters under varying condition. Wind turbine modeling is important, because the performances of the WEGS (wind energy generation system) determine the features offered by the simulator for:

1) Prediction of the energy output;
2) Analysis of the energy conversion and system dynamics;
3) Development of the wind system control strategies.

Several turbine simulators have been created to emulate the wind turbine. Each emulator has its own design based on the operating factors as connection for the grid or stand-alone operation, fixed speed or variable speed turbine, synchronous or induction generator coupling etc. The simplest and the most common approach are to use a basic static torque equation to

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calculate the 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 only capable performing steady state simulations [5]-[7] while others are capable of dynamic simulations [8]-[12]. The majority of previous simulators include the effects of the turbine inertia [5]-[10], which indicates how important it is, although the consequences of neglecting it were not demonstrated. None of the lab simulators reviewed in [5]-[9] include wind shear, tower shadow or pitch angle control effects. This makes these simulators unsuitable for studying any issues that may arise due to the 3p power pulsations resulting from these effects or wind turbine dynamics at high wind speed values.

In this paper the wind turbine simulator includes several important components of which one or more was missing in other simulators. These components are pitch angle controller, turbine inertia, tower shadow model and torsional oscillations. Detailed descriptions of these modeling as well as simulation results are shown in the next sections.

The simulator is capable of evaluating turbine performance under a wide variety of wind conditions. These wind conditions could be developed from wind models emulating conditions that a wind turbine would experience in the site. The simulator could determine the torque oscillations expected under these conditions and allow us to improve the design and operation for the turbine controller. The simulator pitch angle controller is capable of leveling the output power for overrated protection.

II. WIND ENERGY CONVERSION SYSTEMS

There are three main types of wind turbines. The fixed-speed wind turbines with a generator directly connected to the grid is shown in Fig. 1(a). In this type the rotor speed variation is very low, because the only speed variations that can occur are changes in the rotor slip. In case of large wind turbines and/or weak grids, capacitors are added to improve the power factor of the whole system. The variable-speed wind turbines with stator- fed generators or slip-ringed induction generators are shown in Fig. 1(b) and (c).

The stator winding of the direct drive synchronous generator is coupled to the voltage source converter or the diode rectifier. When the back-to-back PWM converters are used, the generator torque is controlled by changing the stator currents through controlling the generator-side converter voltage [11]. The third configuration is a wind turbine with doubly-fed induction generator in which the back-to-back PWM converters feeds the rotor winding. The stator winding of the doubly-fed induction generator is directly connected the grid and the rotor winding is coupled to the gird through the back-to-back PWM converters. The size of the converter does not only relate the total generator power but also the selected speed range and hence the slip power. The converter provides the DFIG the ability of reactive power control. It decouples the active and reactive power control by the independent control of the rotor excitation current. By means of the bi-directional power converter in the rotor circuit, the DFIG is able to work as a generator in both sub-synchronous (positive slip s>0) and super-synchronous (negative slip s<0) operating area [12].

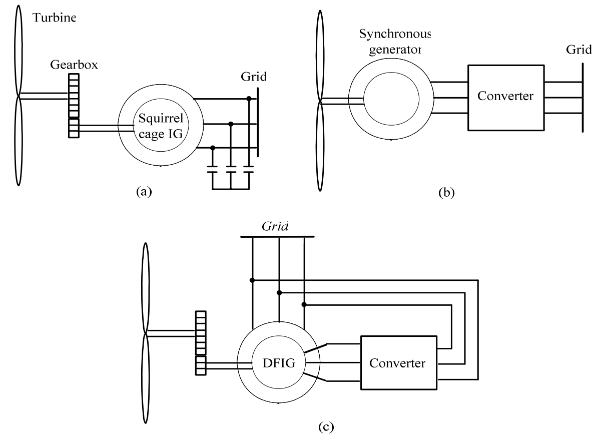

Fig. 1. Wind Energy conversion systems integration.

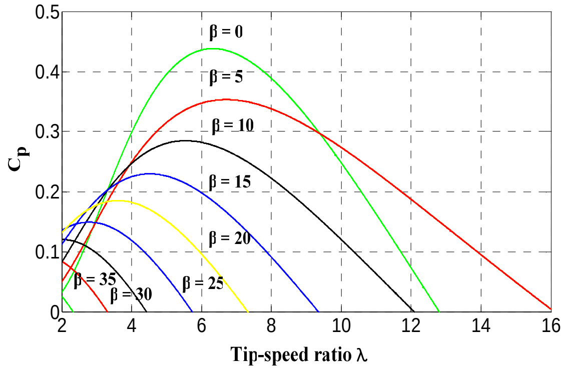

Fig. 2. Wind turbine characteristics at different pitch angle.

III. WIND TURBINE MODEL

The wind turbine can be characterized by its $C_p - \lambda$ curve (as shown in Fig. 2), where the tip-speed ratio λ is defined as the ratio between the linear speed of the tip of the blade to the wind speed. It is shown that the power coefficient C_p varies with the tip-speed ratio. It is assumed that the variable wind turbine is operated at high C_p values most of the time. In a fixed-frequency application, the rotor speed of the induction generator varies by a small percentage (based on the slip) above the synchronous speed while the speed of the wind may vary over a wide range. The power captured by the wind turbine may be written as (1) [12]

$$P_{rot} = \frac{1}{2}\rho\pi R^2 \upsilon^3 C_p(\beta,\lambda) \tag{1}$$

where ρ is the air density, R is the turbine radius, v is the wind speed, and $C_p(\beta,\lambda)$ is the power coefficient, which for variable-speed pitch-controlled wind turbine depends on both the pitch angle β and the tip speed ratio

$$\lambda = \frac{\omega_r\ R}{\upsilon} \tag{2}$$

where ω_r is the blade rotational speed.

From (1), it is apparent that the power production from the wind turbine can be maximized if the system is operated at maximum C_p. From (2), the tip-speed ratio for a fixed-speed wind turbine varies over a wide range depending on the wind speed. The operating regions for the wind turbine are illustrated in Fig. 3. There are two operating regions depending on the wind speed. Below the rated power, the blade pitch angle is set to give the maximum power. The shape of the curve in this region reflects the basic law of power production, in which the power is proportional to the cube of the wind speed. The second region is operated when the wind is sufficiently available for the rated power. In this region the blade pitch angle control regulates the output power to be the rated power of the generator.

IV. DRIVE TRAIN MODEL

The actual wind turbine generation system consists of wind blades, low-speed shaft, gearbox, high-speed shaft, and generator rotor. The complete model of the wind turbine mechanical drive train system can thus be represented by three masses connected by two shafts as shown in Fig. 4(a). The approach adopted here for the analysis of dynamic motion of a mechanical system (i.e. wind turbine drive train system) is that the wind turbine and generator rotor can be modeled as masses, while the wind turbine shafts can be modeled as spring element.

Apart from the difference in the source of energy used in each case, high turbine inertia and low shaft stiffness between the turbine and generator rotor are distinct features of the wind power generation systems. The large difference between the speeds of the turbine and the generator makes a gearbox an essential part of windmill drive train. Obviously, the presence of the gearbox makes it necessary that the two shafts on its either sides, as shown in Fig. 4(a), rotate at different speeds. On the other hand, the presence of the gearbox in wind turbine mechanical drive train results in a wind turbine system that has a small value of mechanical shaft stiffness between the turbine-generator units when it is viewed from the generator side. The three-mass model system shown in Fig. 4(a) can be simplified into a two-mass system by referring the moment of inertia of wind turbine and low-speed shaft masses, stiffness of the low-speed shaft to the generator (high-speed) side.

The simplified model is shown in Fig. 4(b) and the control block diagram in Fig.5. The drive train equations of this two-mass model are [2]

$$T_{total} - T_k = (J_t s + D_t + \frac{k}{s})\omega_r \tag{3}$$

$$T_k - T_g = (J_g s + D_g + \frac{k}{s})\omega_g \tag{4}$$

$$T_k = (\frac{k}{s} + D_{tg})(\omega_r - \omega_g) \tag{5}$$

where T_{total} is the total (rotational and oscillation) torque referred to the shaft, J_t and D_t are the inertia and friction referred to the high shaft, respectively. T_k and T_g are the torque in the flexible coupling and in the electric generator, respectively. J_g and D_g are the inertia and friction of the generator side, respectively.

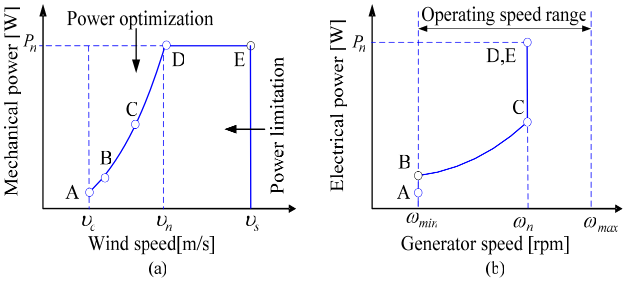

Fig. 3. Power curve in different control modes.

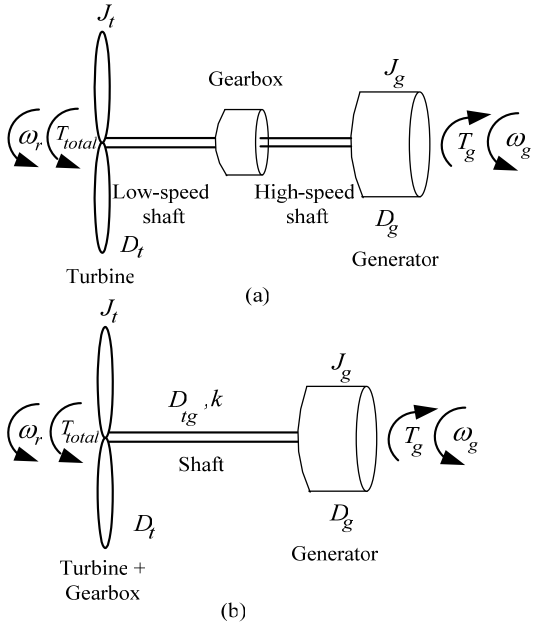

Fig. 4. Modeling of drive train (a) three-mass model of wind turbine (b) two-mass model of wind turbine.

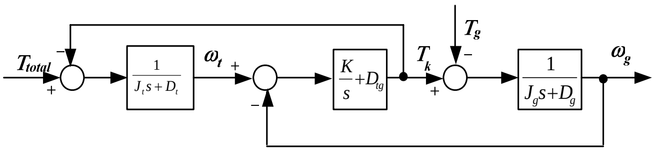

Fig. 5 Transfer function diagram of a two-mass system.

V. TOWER SHADOW EFFECT

As a turbine blade rotates, it is influenced by each wind speed at different heights. The variation of the wind speed with regard to the height is termed as wind shear. Wind speed generally increases with regard to the height. As a result of the difference in the wind speed between the upward blade and the downward, torque pulsations and therefore power pulsations are observed due to the periodic variations of blade pointing upward would encounter the wind speed higher than a blade pointing downward. During each rotation the torque oscillates three times the fundamental frequency 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 blade is located upward or downward of the tower. For upward 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 as shown in Fig.6. For downward 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 the blades downward and the wind is blocked as opposed to redirected. To determine control structures and power quality of issues, the dynamic torque generated by the blades of a wind turbine must be investigated. The turbine blade assembly in the hub can be a source of mechanical oscillation and asymmetry of the turbine blades creates a torque pulsation which goes through the drive train and generator to the grid. It is therefore important to model these blade asymmetry and tower shadow effect which induce torque pulsations for a practical wind turbine simulator.

The variation in the total extracted power P_{total} can be written as a function of the aerodynamic power P_{rot} [2]

$$P_{total} = P_{rot}\left(1+\sum_{k=1}^{2} A_k\left(\sum_{m=1}^{2} a_{km} g_{km}(t) h_k(t)\right)\right) \qquad (6)$$

where $$g_{km}(t) = \sin\left(\int_0^t m\omega_k(\varsigma)d\varsigma + \phi_{km}\right) \qquad (7)$$

where A_k is the magnitude of the k-th kind of eigenswing, ω_k is the eigenfrequency of k-th kind of eigenswing, $h_k(t)$ is the modulation of k-th kind of eigenswing, m is the harmonics, g_{km} is the distribution of k-th kind of eigenswing for the m-th harmonic, a_{km} is the normalized magnitude of g_{km}, ϕ_{km} is the phase of k-th kind of eigenswing for m-th harmonic.

VI. OVERALL SYSTEM

Figure 7 shows the total system overview. At first, the static characteristics of the wind turbine are modeled through (1). The tip-speed ratio λ and power coefficient C_p can be calculated to produce the aerodynamic torque by using the input parameters of υ, ω_r and β. These coefficients are calculated for a 2MW wind turbine in order to give torque values suitable for a desired speed range. The effect of tower shadow and the asymmetrical wind turbine blades are then calculated and added to the aerodynamic torque simultaneously. The static characteristics of wind turbine, tower shadow effect and the blade construction are only the wind wheels characteristics. The coupling between the wheels and generator can be represented using a 2-mass drive train model.

Drive train model includes the effect of turbine inertia, generator inertia, damping coefficients as well as shaft stiffness. Pitch angle of wind turbine blades is controlled in order to maintain the generator power limited to the rated power. The pitch angle is set to the minimum value when the mechanical power is less than the rated value (region AD in Fig.3).

If the wind speed increases higher than the corresponding rated power, the pitch angle will increase to keep the power limited to the rated value (region DE in Fig.3). The blade pitch angle controller consists of the speed and power controllers, of which block diagram is shown in Fig. 7. The speed controller operates at idling, starting and shutdown. At full load, the reference power is set to the rated value, and then a new pitch angle is used to change the blade angle corresponding to the wind speed and limiting the out power to the rated value.

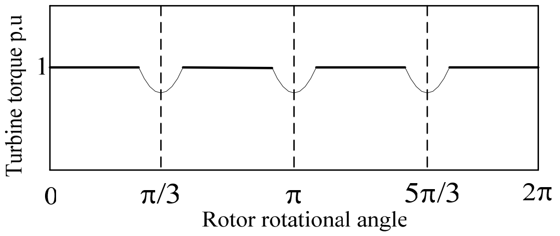

Fig. 6. Tower shadow effect.

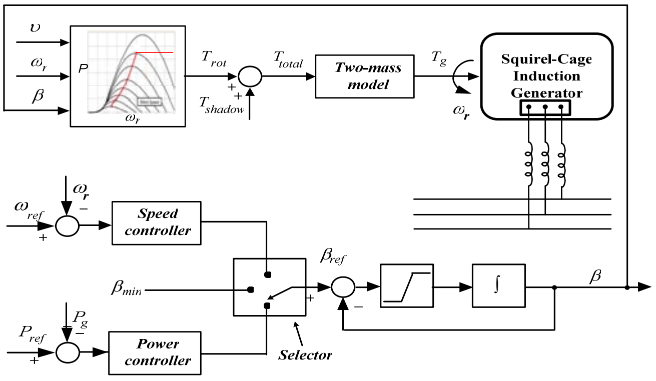

Fig. 7. Block diagram of wind turbine controller.

VII. SIMULATION RESULTS

The proposed model of the wind turbine simulator is implemented by PSCAD software. To evaluate the performance of the pitch controlled wind turbine system, a set of step response simulations with deterministic wind speed (no turbulence, no tower shadow) are performed, of which results are shown in Fig. 8. At wind speed lower than 13[m/s], the pitch angle controller is deactivated, keeping the pitch angle constant to the minimum value. The generator power and speed are continuously increased as the wind speed increases. At wind speed higher than 13[m/s], the pitch angle controller is activated and limits the output power to the rated value. In the power limitation case, the responses of the generator speed and power show, due to large step wind speed variation, a remarkable overshoot and oscillation as shown in Fig. 9.

Figure 10 shows the response of the system at constant wind speed of 11[m/s] with gust amplitude of 4[m/s]. The pitch angle controller is deactivated at low wind speed and activated at high wind speed. The power is limited to the rated value of 2[MW]. The response for repetitive wind gusts with amplitude of 2[m/s] is shown in Fig. 11. It is also clear that the generator speed in a small range. The tower shadow and blade asymmetry induced a pulsating torque which is approximately 4% of the rated torque. These oscillations were significant to cause a resultant fluctuation in the output power and torque as shown in Fig. 12 and 13. The effect of the tower shadow is also obvious in the generator power oscillations and the pitch angle oscillations from Fig. 8 to Fig. 11. It can be observed that the tower shadow oscillation frequency is as low as about 2 Hz.

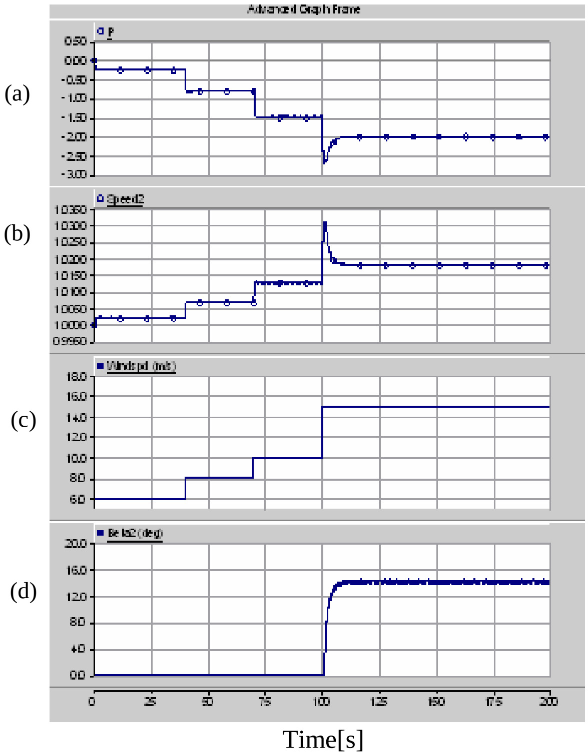

Fig. 8. Step variation of wind speed.
(a) Generator output power, (b) Generator speed,
(c) Wind speed, (d) Pitch angle.

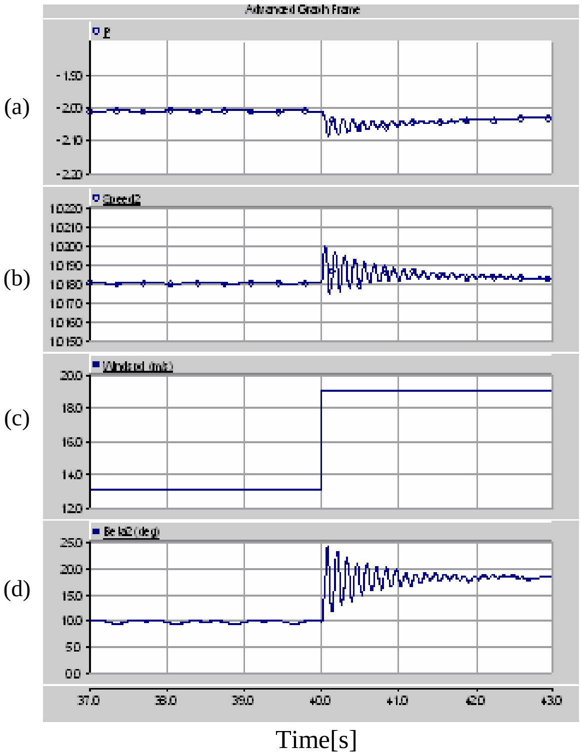

Fig. 9. Large-step variation of wind speed.
(a) Generator output power, (b) Generator speed,
(c) Wind speed, (d) Pitch angle.

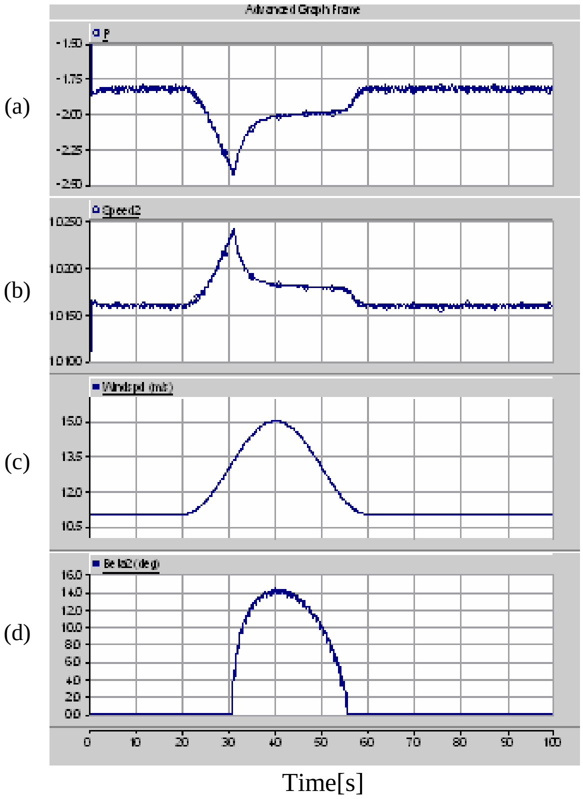

Fig. 10. Wind turbine performance during gust with 4[m/s] amplitude and 40[sec] duration: (a) Generator output power, (b) Generator speed, (c) Wind speed, (d) Pitch angle.

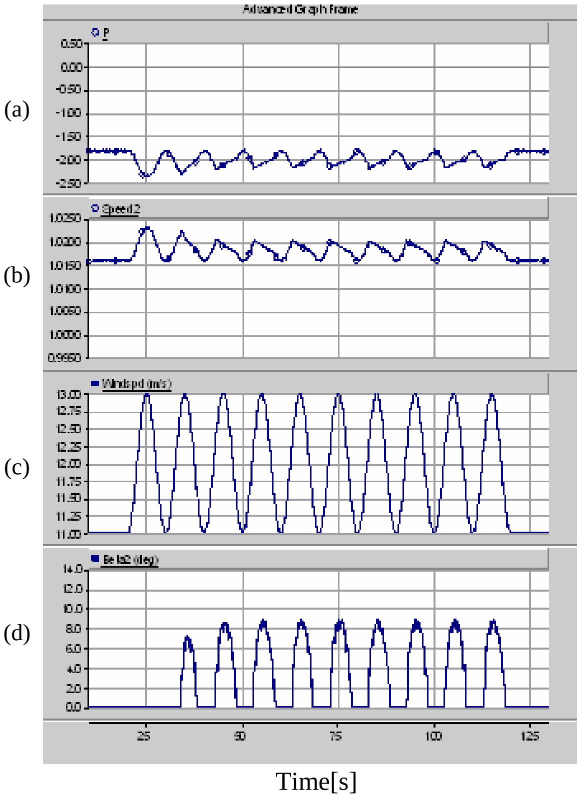

Fig. 11. Wind turbine performance for repetitive gusts 2[m/s] amplitude and 10[sec] duration: (a) Generator output power, (b) Generator speed, (c) Wind speed, (d) Pitch angle.

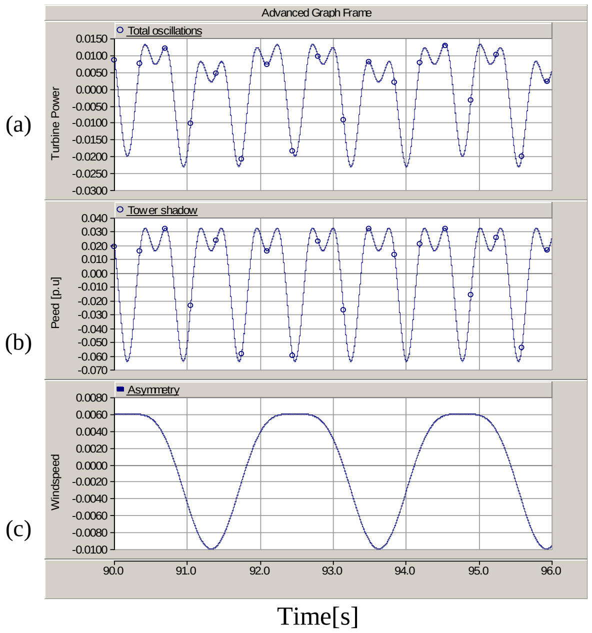

Fig. 12. Torque oscillations. (a) Total torque oscillations, (b) Tower shadow effect, (c) Asymmetric blade effect.

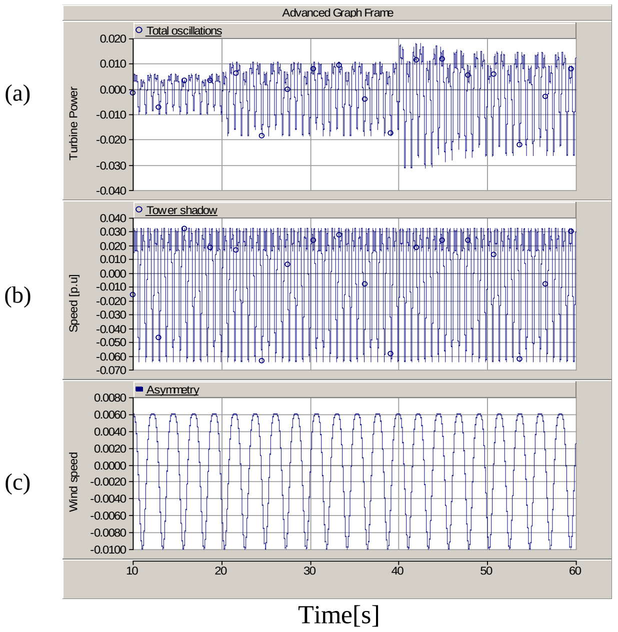

Fig. 13. Torque oscillations. (a) Total torque oscillations, (b) Tower shadow effect, (c) Asymmetric blade effect.

VIII. CONCLUSIONS

A dynamic modeling for wind turbine simulator has been implemented for computer simulation study using PSCAD software. The wind turbine and its controllers have been built using the built-in components provided by PSCAD tools. The tower shadow and blade asymmetry have been constructed using the existing functions. Wind source, wind turbine model, drive train and squirrel cage induction generator have been simulated to successfully represent the effect of wind speed variation, tower shadow, blade asymmetry, large turbine rotor inertia and power limitation control. At low wind speed, the pitch angle controller is deactivated and the generator output power is proportional to the cubic value of the wind speed. At high wind speed, the pitch angle controller limits the generator output power to the rated value. The tower shadow effect was shown to cause a predictable depression in turbine torque that was transferred to the generator and seen in generator output power. The transmission of this torque fluctuation was shown to be less severe in cases where large turbine rotor inertia was included in the simulation. The effect of variable wind and the power fluctuation produced were also shown to be smoothed by large turbine rotor inertia. The proposed wind turbine simulator can be used for simulation of practical wind power generation.

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