Analyzing the Static and Dynamic Characteristics of Wind Energy Conversion System Using Wind Turbine Simulator

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***Abstract*— The static and dynamic characteristics of wind energy conversion system (WECS) are presented in this paper. For this purpose, a wind turbine simulator (WTS) is designed and developed using MATLAB/Simulink. The actual wind turbine is replaced with a DC motor in order to replicate the speed and/or torque. The intelligent DC-DC power converter of half-bridge type has been designed to drive the motor in controlled way. Two different control structures, for static and the dynamic characteristic replication separately, have been designed. Isolated WECS of the type fixed-pitch with the structure horizontal axis wind turbine (HAWT) having three blades is opted for the modeling and performance analysis of the proposed WTS. The obtained simulation results confirm that the developed WTS is able to mimic the static as well as dynamic characteristics of the real WECS. The system design, the models developed and the results along with analysis, are presented in this paper.**

Keywords (control system, DC motor, wind energy conversion system, wind shear, tower shadow effects, wind turbine simulator)

NOMENCLATURE

A	Rotor swept area	(m^2)
C_p	Power coefficient	f (λ, β)
PQ	Power Quality	-
P_m	Mechanical output power	(watt)
R	Rotor radius	(m)
T	Torque	(N-m)
ρ	Air density	(kg/m^3)
v	Wind speed	(m/s)
β	Blade pitch angle	(deg)
λ	Tip Speed Ratio (TSR)	-
ω	Rotor speed	(rad/sec)

I. INTRODUCTION

The natural wind is primary input source to any wind energy conversion system (WECS) and it is a known fact that the wind has intermittent nature, with haphazard variations and because of being natural it is uncontrollable therefore causes the wind turbine to deliver variable output power, so does the coupled generator. Furthermore, because of the intermittent nature, it causes fluctuations in the output and hence results the power quality (PQ) issues. Hence, it becomes inevitable that, real WECS to be installed should be analyzed prior to the installing at the field. In this regard, design and realization of a wind turbine emulator/simulator plays a vital role. In general, a wind turbine emulator/simulator is a laboratory based test setup. It mimics the real WECS, therefore offers the researchers and academicians to conduct the research on WECS, in a controlled environment. For designing as well as validating the control algorithm of the WECS the WTS plays a vigorous role [1]. It can also be employed for analysis of the machine side converter (MSC) and load side converter (LSC) of the WECS. Furthermore, it is also employed to examine and validate the generator control algorithms [2]. For developing and validating the pitch control mechanism WTS can also be strong candidate. Above all, its vital for analysing the performance of WECs.

Literature review reveals that other researchers have designed and developed such test-benches [1-19]. The fundamental aspect for designing a WTS is the electrical motor, which is deployed to replicate the behaviour of real wind turbine by reproducing the speed and/or torque. In this regard, some authors have used DC motor [3, 4, 8, 19-23] and others have opted induction motor (IM) [7, 24, 25].

Furthermore, some examples can be found in literature on modelling the effect of inertia [26-28]. A detailed study reveals that that there are also many models in which the higher order effects, i.e. shaft elasticity as well as gearbox inertia have been considered [2], [27]. However, the important factor is, the static and dynamic characteristics of the simulation/emulation system must resemble as close as possible to that of an actual wind turbine. It has been witnessed from the available literature, in case of low speed; a DC motor can accurately replicate the wind turbine's behaviour. On contrary, an AC motor is not a good choice if operated below 1/3 of its base speed, the reason is, it cannot mimic properly the actual turbine characteristics below one third of its base speed [4]. Keeping in view the above fact, a separately excited DC motor is opted to replicate the behaviour of the real wind turbine.

Most of the aforementioned publications found are based on hardware design. This paper is completely based on simulation, offering quite flexibility and hence one can easily reproduce. One of the main purposes of this paper is to present the design and development of the proposed test-bench. The development of simulink model of the wind turbine considering the fundamental equations, control system structure, feedback mechanism, design of controlled power converter, PWM signal generation and controlling the output voltage, are described in detail. Two different simulink models have been developed and implemented on the proposed WTS. Firstly, static characteristics of the WECS are imitated. Then the dynamic behaviour of the wind turbine is analysed. Hence, the contribution of the paper can be highlighted as, the proposed WTS is able to mimic the static as well as dynamic characteristics of the real WECS. In case of dynamic characteristics, the influence of wind shear and tower shadow has been investigated. The proposed and developed WTS will provide the researchers a platform for conducting studies in the field of WECS in a controllable test environment without the real wind turbine and natural source. Above all, the paper also aims at describing the extended description of development of a complete setup.

The rest of the paper is structured as follows. The section II is dedicated to describing wind turbine along with associated mathematical equations. The proposed WTS is explained in section III. The section IV contains simulation results and analysis. Finally, the conclusion of the paper is presented in section V.

II. Wind Turbine and its Characteristics

Wind turbine is the most important component of any WECS. The basics of mathematical modelling are extensively available in literature [2] [4] [5].

The output mechanical power of three-bladed HAWT is generally given by,

$$P_m = 0.5\rho\pi R^2 C_p(\lambda,\beta)v^3 \quad (1)$$

here, πR^2 denotes the swept area of the rotor; which means, equation (1) can also be expressed as,

$$P_m = 0.5\rho A C_p(\lambda,\beta)v^3 \quad (2)$$

whereas,

$$C_p(\lambda) = 0.00044\lambda^4 - 0.012\lambda^3 + 0.097\lambda^2 - 0.2\lambda + 0.11 \quad (3)$$

here, λ is tip speed ratio (TSR) and β indicates the pitch angle of the blade, whereas λ is given by,

$$\lambda = \frac{\omega R}{v} \quad (4)$$

ω being turbine angular velocity (rad/sec) and v is denotes the wind velocity (m/s). In case of small and medium WECS, β the pitch angle is usually maintained fixed.

The average torque developed by the wind turbine is described as,

$$T = \frac{P_m}{\omega} \quad (5)$$

Therefore,

$$T = \frac{0.5\rho A C_p(\lambda,\beta)v^3}{\omega} \quad (6)$$

The C_p -λ curve is widely available in the published literature.

$$\omega = \frac{0.5\rho A C_p(\lambda,\beta)v^3}{T} \quad (7)$$

The speed described in equation (7) plays the role of reference value of the rotor in a specific wind speed. It has been witnessed from the literature that different researchers, designers have used different approaches to calculate the C_p. In this paper, the calculation of Cp has been taken from [4, 21, 29].

Furthermore, according to the [3, 30], the torque pulsations due to wind shear and tower shadow influences, can be presented as,

$$T_{mech} = [T_{mill}\ 1 + A_1 \sin(\omega_{mill} t) + A_3 \sin(3\omega_{mill} t)] \quad (8)$$

Where A_1=0.2 & A_3=0.4

T_{mech} and T_{mill} are the aerodynamic and average torques of the wind turbine correspondingly. For dynamic analysis, instead of taking average value of the torque, the pulsations in torque have been considered.

III. THE PROPOSED WIND TURBINE SIMULATOR

The developed WTS, as depicted in the Fig.1, primarily consists of a DC motor, controlled half-bridge DC-DC power converter, permanent magnet synchronous generator (PMSG), electrical load and DC power supply. In the developed WTS, the actual wind turbine is replaced by a DC motor. The motor, which is source of generating reference speed and/or torque, is driven by controlled power converter. First of all, a simulink model was developed in MATLAB considering the static characteristics of the wind turbine, which provided the reference signal. As explained in the section II, apart from the rotor radius, air density and wind speed, the reference value also varies with respect to the feedback signals. Apart from the development of simulink model based on wind turbine characteristics, speed and current controller (both PI controllers) were also designed in MATLAB/Simulink development environment. The reference speed calculated, was used a reference value for the speed controller. In section C, control system structure is explained in detail. A comparator which compared the the control signal with the triangular wave form, was used and the PWM signals were generated and sent to the gate for triggering the IGBT switches of the DC-DC power converter. It is important to mention here that for the lower switch of the DC-DC power converter, the compliment (not) signal was generated.

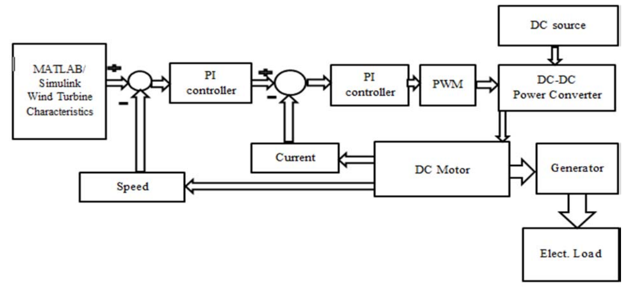

Fig.1. The proposed wind turbine simulator

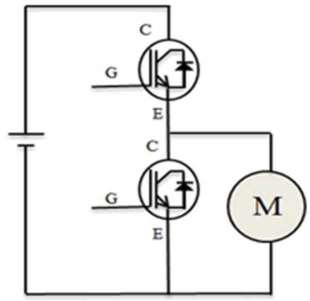

Fig.3. The developed DC-DC power converter

The controlled output voltage of the converter was supplied to the separately excited DC motor. In section B. description of the DC-DC converter is provided. Based on the control signal, the duty cycle was calculated and command was sent in order to generate PWM signal, which in turn yielded control signals (gating pulses) for the IGBT devices of the power converter. Two machines- DC motor and PMSG -were back to back connected, motor replicating the turbine and the PMSG considered as in real WECS. Once the complete system was developed, the DC motor could successfully mimic the behavior of the actual WECS, with specific characteristics of the wind turbine.

A. DEVELOPMENT OF SIMULINK MODEL

Two different simulink models were developed. First, to replicate the static characteristics of the real WECS. For this purpose, based on turbine characteristics, the simulink model

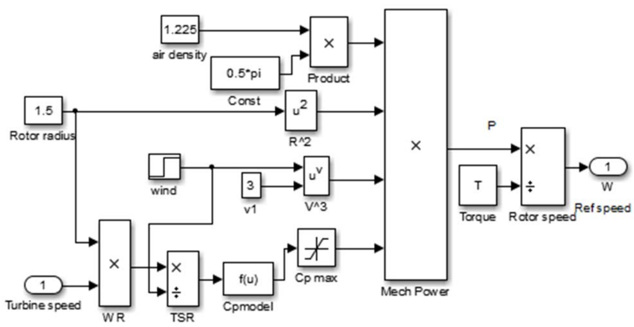

Fig.2. The simulink model

was developed as shown in the Fig.2. The speed was considered as the reference value for the WTS. In second case, the simulink model was developed to generate the reference torque. In later case, the dynamic effect because of the wind shear and tower shadow was considered.

B. DC-DC POWER CONVERTER

The designed DC-DC power converter is shown in the Fig.3. It consists of two IGBT switches, upper and the lower, connected in a way as that form half-bridge.

The DC-DC power converter was supplied 75V DC as input. The controlled output voltage was connected with armature terminals of the DC motor. Since, separately excited DC motor has been used, therefore; 50 V DC was supplied for the excitation. The PWM signals were produced and these signals were sent to trigger the gates of the IGBTs. The duty cycles were controlled such that the upper IGBT received PWM signal whereas the lower IGBT received its compliment (not signals).

C. CONTROL SYSTEM STRUCTURE

For the static characteristics, the cascaded closed loop control system based on tow PI controllers was used, i.e. the speed controller and the current controller. The calculated speed was used as the reference value for the outer controller. By comparing the reference value with the measured one, the outer controller sends error to the inner controller. The inner controller compares the actual current and the reference signal and generates the command signal for duty cycle calculation, and hence the PWM signals are generated depending upon the duty cycle calculated. Consequently, with this setup, mainly with the controlled power converter, the DC motor accurately reproduces the characteristics of the actual turbine.

In case of dynamic characteristics, only a single PI controller (torque) was employed, as shown in the Fig.*4.* The reference torque was calculated, considering the dynamics caused by the wind shear

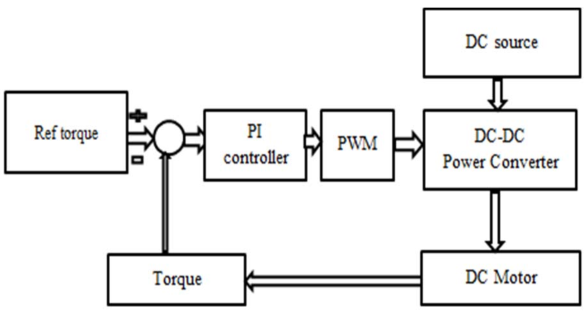

Fig.4. Control system structure for dynamic characteristics

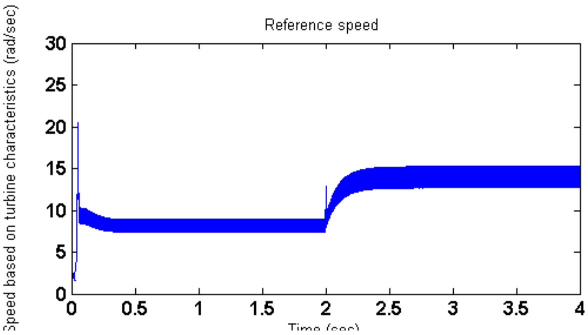

Fig.5. Reference speed (rad/sec) based on turbine characteristics

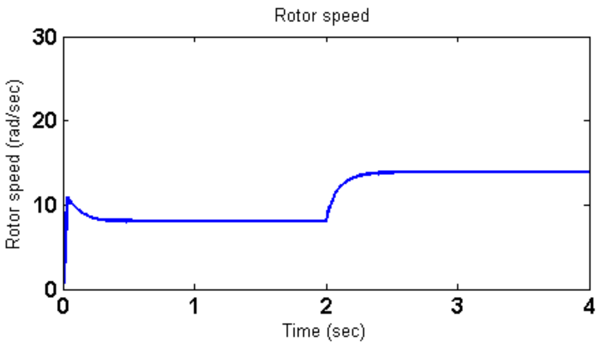

Fig..6. Rotor speed (rad/sec)

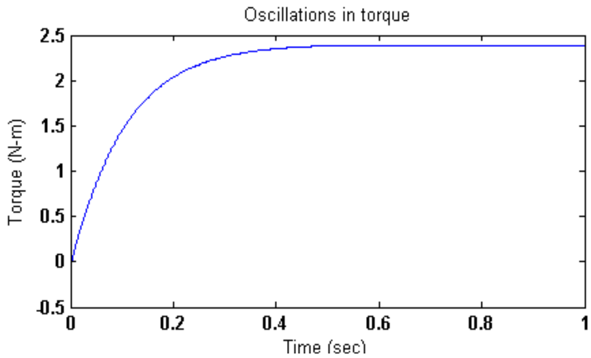

Fig..7. The torque (N-m)

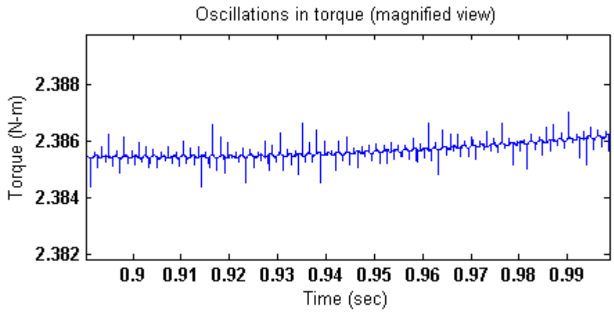

Fig..8. The oscillations in produced torque

IV. SIMULATION RESULTS

The proposed and developed WTS was investigated under different conditions for the performance analysis. Initially, a simulink model was developed based on the characteristics of wind turbine. In this case, wind speed with step change was applied, i.e., initially 5 ms^{-1} and at t=2 seconds, it was changed to 6 ms^{-1}. The air density, taking into account the practical value, was chosen as 1.225 kg/m^3, 1.5 m was considered the radius of the turbine rotor and the C_p (power co-efficient) was used as described in section II. The respective simulation results are described as here. The Fig.5 shows the reference speed taken into account the characteristics of wind turbine and the Fig.6 shows the speed of the rotor. Furthermore, the same developed WTS was used to investigate the wind shear and tower shadow effects. For this purpose, another simulink model, considering the aforementioned effects, was developed and results were obtained. Fig.7 shows the generator torque. As it can be witnessed from the Fig.8 that the wind shear and tower shadow effects cause oscillations in the toque. It should be noted that, as shown in the Fig. the model was run for one second only.

V. CONCLUSION

The real wind turbine is replaced by a separately excited DC motor. The DC motor has been driven by PWM based controlled half-bridge DC-DC power converter. Thus, the developed wind turbine simulator (WTS) has been designed and developed which imitates the real and isolated wind energy conversion system (WECS). The complete WTS comprising of model representing the turbine characteristics, digital PI controllers as well as the power converter have been developed on MATLAB/Simulink platform. Two different models, describing static and dynamic characteristics of the real WECS, have been developed. Two different control approaches for both the cases have been used.

The obtained simulation results witness the effectiveness of the designed and developed model. It has been witnessed that the wind shear and tower shadow effect cause fluctuation in the torque. This modeling approach can further be used for MPPT algorithms, generator control technique and analyzing the performance of power electronics.

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