Wind Turbine Emulator Implementation using FPGA

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Abstract: ***In wind energy technology, a wind turbine is used to convert the kinetic energy of wind to mechanical energy. Due to its bulky nature and top height, study of wind turbines has become troublesome. Moreover, arbitrary nature of wind adds to the problem. For this paper, study and performance analysis of the wind turbine under various wind speed and pitch angle is done by creating a model, called wind turbine emulator. Here, the model is realized through a separately excited dc motor operating with a dc-dc converter circuit and controlled through pulses generated using FPGA. Thus, motor drive is made to behave like a wind turbine. A dc generator is coupled to the motor. The motor rotates the generator. Validation of the suggested model is done through analysis of the torque and power responses for various wind speeds, comparison of the emulator's performance with established wind turbine characteristics based on design specification.***

Keywords: Wind energy, Wind Turbine, Wind Turbine Emulator, FPGA Controller

1. Introduction

Energy serves as a backbone of our economy. Burning fossil fuels are one of the most important non-renewable sources of energy. But fossil fuels are harmful to nature and they increase the carbon emission causing global warming etc. Even now, they are used widely to produce electrical energy. But the over exploitation of fossil fuel have led to global warming, climatic change and increase in pollution. However, in recent decade the demand for electrical energy has rapidly increased worldwide. This led to the advancements in field of electrical energy production from renewable energy source. Wind has shown the second fastest growth in terms of installed capacity worldwide [1]. A country like India or any region where energy production is based on imported coal or oil, will become more self-sufficient by using alternatives such as wind power. In remote areas or areas with a weak grid, wind energy can be used for charging batteries or can be combined with a diesel engine to save fuel whenever wind is available. At windy sites the price of electricity, measured in Rs/kWh, is competitive with the production price from more conventional methods [2]. As we all know, wind is a renewable source of energy which is in-exhaustible. In the last couple of years, various technologies are developed which reduce the cost of production of energy by harnessing wind. Many technologies have been developed to produce energy more efficiently from wind. One of the most important technology was the discovery of Wind Turbine [WT]. This was a major breakthrough in developing clean energy without affecting the nature and that too cost effectively. They are huge metallic frames that are attached together to form a single WT. They are large in size and hard to transport with installation cost about 4.5 to 5 crores [3]. Thus, a new concept, Wind Turbine Emulator (WTE) has introduced, which is significant

An emulator simulates the operation and purpose of wind turbine and enable researchers to set up model of WECS in laboratories for the research purpose. The basic aim of this type of equipment's is to determine static and dynamic characteristics of an actual wind turbine. WTE are evolved using different types of control practices and motors. When separately excited motors are used in wind turbine emulators then the control techniques used are voltage control technique or field current control technique to get the characteristics of a WT. The relationship between wind speed, air density, turbine rotational speed, and swept area is used to depict the mechanical power and torque production of the turbine. The development of a WTE is based on these relationships. The use of an electric motor drive directly linked to the generator shaft is the most practical method for simulating the behavior of a wind turbine in a laboratory. In general, a DC motor is a preferable option for a WTE since the armature current, which is directly proportional to the torque the machine produces, can be used to operate it. The two major types of motors used in WTE are DC motor and induction motor of this DC motor is the most ideal one. Additionally, the DC motor is easy to regulate and has excellent dynamic properties. Because DC motors are bulkier and need more regular periodic maintenance due to the presence of collecting brushes, a static power converter must be used for this purpose in order to manage the torque. Simulation techniques have been employed in real-time simulations of wind turbines to solve the issues caused by the use of DC motors. Additionally, three-phase induction motors, which are more effective, cheaper, smaller, and require less frequent periodic maintenance than DC motors, have also been employed in WTE applications. Despite these benefits over the usage of DC motors in WE, using three phase induction motor has additional drawbacks, such as the production of audible noise and the requirement for power converters to regulate the machine, which drives up expenses.

2. Wind Turbine Emulator Description

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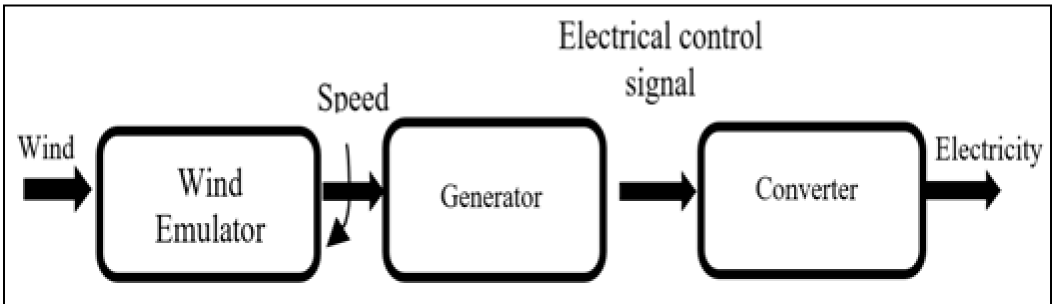


Wind energy conversion

Several improvements were made to the conversion structures to model and tighten the control of their operations depending on weather conditions in order to make simulations and the deployment of the emulator feasible. The general structure of the proposed wind emulator is shown in Figure 2..Being conscious of the energy present in wind kinetic energy, The wind turbine's capacity forcatching the wind will never be entirely extracted, it essentially consists of a power electronics stage, a wind turbine simulator based on a wind profile, a turbine model, and DC motor. Wind energy is represented by the power coefficient Cp.

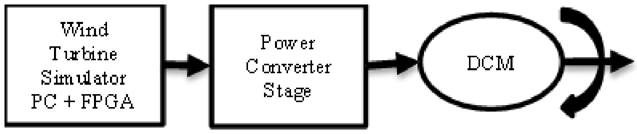
The tip speed ratio, which determines the Cp phrase in consumption, is stated as follows:

$$Cp(\lambda) = -3.7e-5\lambda^3 - 0.004834\lambda^2 + 0.1063\lambda - 0.02086 \quad (1)$$

Turbine mechanical power, the rotor speed and the turbine mechanical torque are given by

$$P_t(V, \lambda) = 0.5\rho S V^3 C_p(\lambda) \quad (2)$$

where ρ is the density of air, S is the surface swept by the wind turbine blades and V is the wind speed



Proposed WTE system

Wind profile

A particular moment's wind speed may be dissected down into an average component, a slowly variable component, and occasional variations. The optimum method for modeling wind speed has been found to be a historical series of measurement data [4].Mathematical wind speed models are interesting for the analysis and implementation of wind variation in a numerical support. The Weibull's distribution, the composite model that incorporates average speed, ramp, gust, and turbulence, as well as the Mexican hat wavelet model, are only a few examples of the several types of wind speed models that are explained in depth [5].

Linear profiles of wind speed is illustrated by Figure in order to validate the theoretical behavior of the proposed wind emulator.

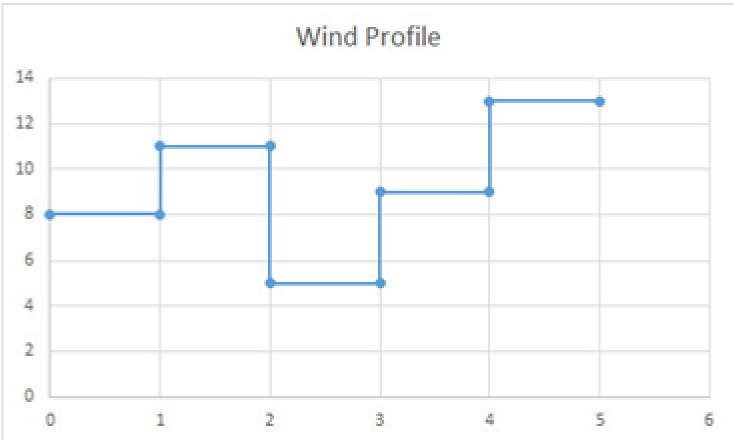


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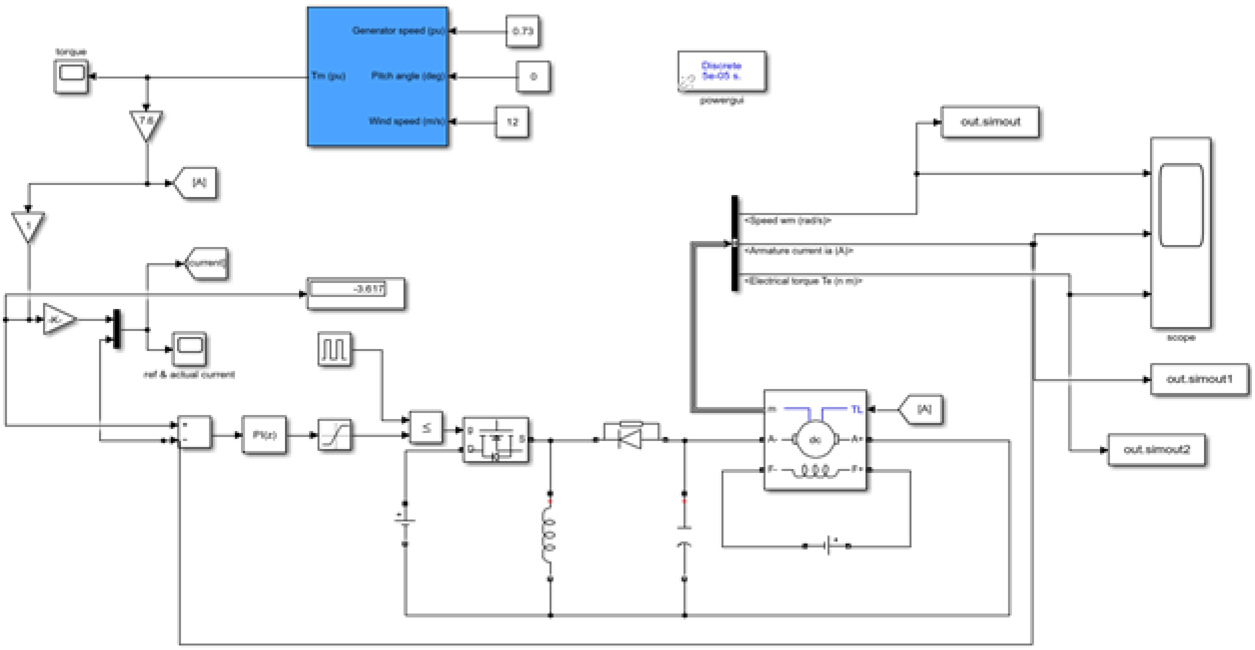
Table 1: Components Required

Components	Specifications
DC Shunt Motor	P = 0.25 HP, V = 230 V, I = 1 A, N = 1500 RPM
DC Shunt Generator	P = 0.81 HP, V = 230 V, I = 0.8 A, N=1500 RPM
Buck-Boost Converter Stack (Switch)	Description: DC-DC Converter V_{dc} input = 600V(Buck), 430V(Boost) V_{dc} output = 600V(Boost), 430V(Buck) I_{dc}= 30 A, Switching Frequency = 20kHz
Inductor	N = 137, L = 50 mH (1 kHz)
Capacitor	60 µF, 440 V
Diode	10A10
FPGA board	DE0 Nano Cyclone IV FPGA Development Board
Rheostat	300 ohms, 5A
Speed Sensor	Hall Effect Sensor
CRO	

3. Software Tools Utilisation for Wind Turbine Simulator Designing

The aerodynamic and mechanical components of the actual wind turbine are theoretically modelled using the MATLAB environment. It is possible to quickly develop a wind turbine simulator model to implement on an FPGA board thanks to the MATLAB/Simulink ecosystem. The related blocks reflect the mathematical equations for the wind profile, wind turbine, duty cycle calculator, and pulse generator. The simulations were run to demonstrate the potential of the suggested emulator with an open loop for simulating the static and dynamic behavior of wind turbines.The armature current and electromagnetic torque of the DC motor are more sensitive to the wind speed oscillation than the motor rotational speed due to their variation rapidity versus the speed response, which is quasi-slow and explained by the motor inertia. Electrical time constant is also faster than mechanical time constant.

The Betz limit is 59.3%, which is the maximum value of the power coefficient [6]. The efficiency of a wind turbine is determined by the power coefficient performance, which measures how much power the wind turbine absorbs and uses.



Simulink model of wind turbine emulator

The simulation model of proposed WTE is shown in figure .From the turbine model a reference torque is generated which is then multiplied with a suitable gear ratio and torque constant to get a reference current. This reference current is compared with the actual armature current of dc motor and the error is minimized using a PI controller. The PI type of controller is used in this scheme because it is easy and very quick to implement. The output of PI controller block is then compared with a very high frequency signal (ramp) to generate pulse width modulated gate pulses to drive a IGBT/MOSFET. This converter controls the armature voltage of dc motor which in turn controls armature current in compliance with the reference current and hence slowly the system attains steady state.Power coefficient defines the maximum amount of energy that can be extracted from the wind by a wind turbine, and a high value is required to effectively use wind power. The power coefficient can be calculated with the help of tip speed ratio. The power coefficient reaches its highest value, or around 0.48, at 8. Certain algorithms are employed to extract the maximum amount of energy from the wind, which in this case is 0.48, or around 48% of energy, so that power is created continuously at its peak.

Experimental Test Bench

The hardware for WTE system is developed using a 0.25 Horse Power (HP) dc motor coupled to a 0.81 HP dc generator. A PI controller is used regularising the output with the help of speed taken as feedback. The whole process is monitored by FPGA. The motor is connected to a converter and further coupled to a synchronous generator. Generally the hardware system comprises of a WTS, a converter, a motor and a generator. The WTS mainly comprises of the computer software and FPGA.The controller part of the WTE is formed using a FPGA.Creating a relation between wind speed and duty cycle, PWM signals are generated. The code is created in Verilog HDL. Further, a closed loop configuration is introduced, taking motor speed as feedback using a hall effect sensor. The signals from sensor are converted to RPM using a frequency counter. An error is calculated between the feedback speed signal and reference speed signal. This error signal is sent to a PI controller developed in FPGA. PI controller transforms the error value to zero and conditioned PWM signal is fed to the converter. The major goal of this system is to maintain constant turbine speed and power generation even when loads are increased.

Experimental equipment for the proposed system

Working

For the input, a wind profile is fed to the system. Wind profile is the representation of various wind speed in a timely manner of a particular location. The hardware system comprises of a dc shunt motor as turbine, dc generator for power generation, FPGA for input signal and controller and dc-dc converter. Dc dc converter is assembled using an bidirectional converter stack, inductor, capacitor and a diode. The bidirectional

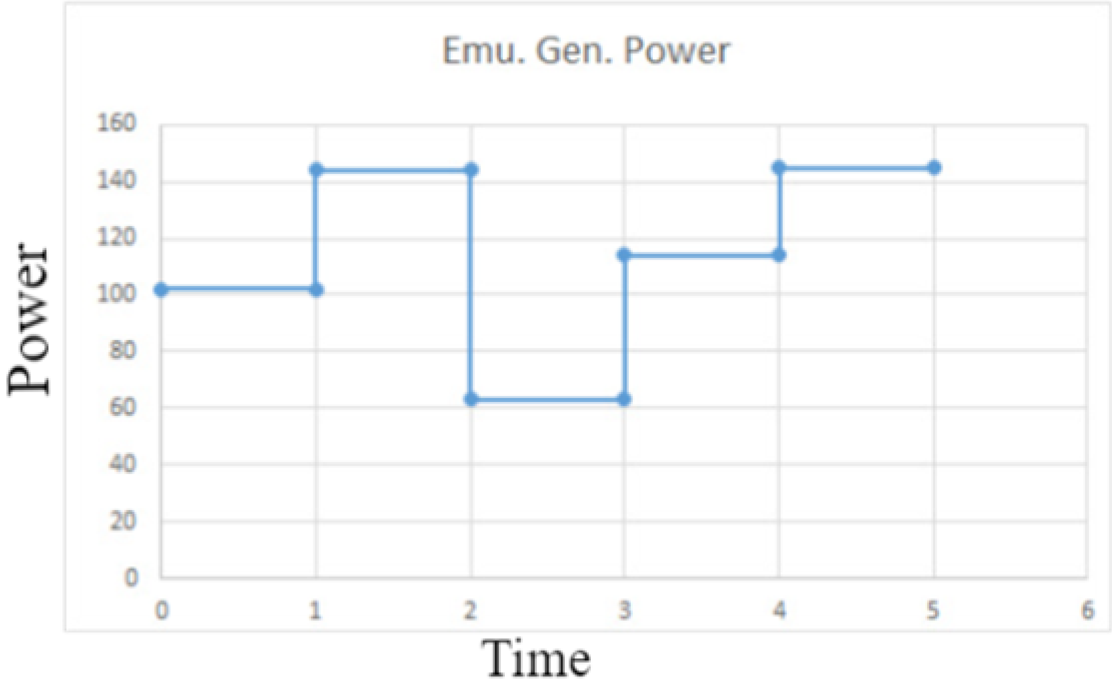
converter stack provides the switch for the converter. A dc 220 V supply is provided to the system as input. We tested our machine under certain condition, for understanding the operating range of machine. From the hardware setup, the power speed and power coefficient curve is obtained. The hardware system developed and operated is shown in figure 7.A turbine functions with a limit between the cut-in speed and cut-out speed. For the project purpose, turbine has its cut-in speed of 5 m/s and a cut- out speed of 15 m/s. Thus wind speed is limited to a range between 5 m/s to 15 m/s.For soft starting, the duty ratio is varied from 0 to 48% over a duration of 48 seconds. After 48 seconds, a PWM of 46% is given to system to run motor in its rated voltage for a period of 30 seconds.This ensures proper starting of the motor PWM signals of various duty ratios are supplied consecutively corresponding to the input wind speeds , each for 60 seconds

Table 2: Relation of wind speed and dutycycle

Wind Speed (m/s)	Duty Ratio	Output Voltage (V)
15	0.5	220
14	0.488	210
13	0.476	200
12	0.463	190
11	0.45	180
10	0.436	170
9	0.421	160
8	0.405	150
7	0.389	140
6	0.371	130
5	0.353	120

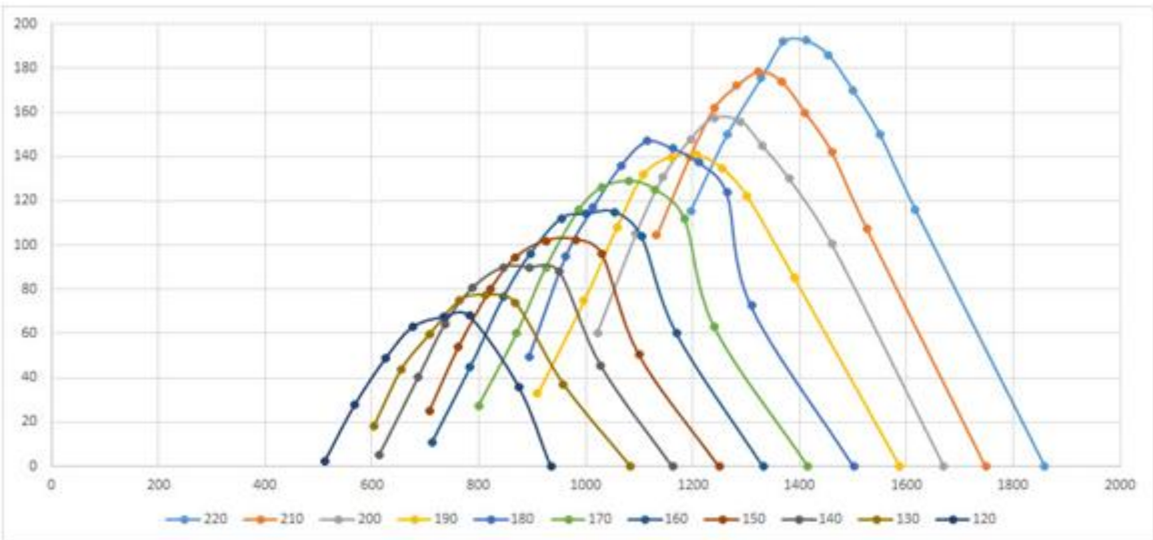
4. Results

The variations in wind speed is set with limiting or linking output voltage of the system. This is shown in table 2.Output voltage is ranged between 220 – 120 V for its operation, for a voltage below cut-in speed the machine fails to work satisfactorily as of a turbine and a voltage above cut-out speed, machine rotates above rated speed



Generated power output of the WTE

Causing damage, with this relation duty ratio is calculated.For a wind speed of 11 m/s, duty ratio calculates to 44% and for 9 m/s to 42%. A duty cycle corresponding to the applied wind speed is generated by the FPGA, which is fed to the converter. The relation with wind speed and duty cycle is obtained through tests performed on the dc motor. The speed of the turbine changes in proportional to wind speed, causing variation to the system parameters. This cause power emulated from the system to change accordingly. The machine was tested under its generic condition. Operating range of machine was set to 1.75.The power is obtained for various wind speed and the waveform is plotted . Figure. 9 shows the variation in emulator generated power in accordance to the input provided to system.Maximum power output obtained from generator is approximately 158 W, for a wind speed of 13 m/s.Motor rotates over a speed of 1240 RPM with an output power of 405 W .



Power speed curve of WTE

5. Conclusion

The WTE is designed for its primary function to mimic the dynamic torque behaviour of a wind turbine and to share mechanical traits with the real thing. Using MATLAB/Simulink, a WTE system is developed and its characteristics for a fixed speed is obtained. A hardware system which is dependent on wind speed and other performance parameters of WT is developed. This WTE can be used as a tool to determine the change in power generation characteristics for a proposed wind speed. The steady state and dynamic characteristic of turbine are emulated using dc motor and torque-speed and power-speed behaviour of wind turbine model are studied. The controller and controlling techniques with the machine used in simulation and hardware are discussed. A buck boost converter is used to control the armature voltage of dc motor and a PI regulator is used to regulate and to minimise the current error. This wind emulator is connected with a dc generator and works in change to wind speed.

6. Future Scope

DC motor is used in the current scheme of project. Other AC machines like induction motor, synchronous motor or servo motor can be used to build a wind turbine emulator with different controlling schemes.

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