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# Optimizing Electrical Generators of Wind Energy Conversion System for Efficient Power Extraction

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**Abstract**

Wind power generation capacity in India has significantly increased over the few decades and the total installed wind power capacity has grown up to 32.72 GW (as on October 2017), which ranks fourth largest in the world. The scope for wind farm as assessed using Geographic Information System (GIS) platform is found to be more than 2000 GW. So there is a lot of scope for expansion wind power projects provided studies are conducted on the selection of its components. One of the main components of Wind Energy Conversion System (WECS) is the electrical generator apart from the prime mover and other structural parts. This paper introduces an experimental setup for the study of different types of electrical generators and their feasibility for different wind conditions. In this setup, Squirrel Cage Induction Generator (SCIG), Slip Ring Induction Generator (SRIG), Permanent Magnet Synchronous Generator (PMSG) and Permanent Magnet DC Generator (PMDC) are available for study. These generators are coupled to a Separately Excited DC motor via a portable coupling arrangement. The separately excited DC motor emulates the wind turbine. The results of the experimental setup are validated and presented.

## 1. INTRODUCTION

Energy serves as the key factor for development of any country. Energy demand for the time being is mostly met by fossil fuels. At the present rate of consumption, the fossil fuels will get exhausted within few decades. Moreover carbon emission adversely affects the climatic condition [1]. Therefore it is high time to replace fossil fuel by renewable source of energy to meet the ever increasing energy demand.

Microgrids can be thought of as, small-scale versions of the conventional grid. They attain specific aims (in small geographic region), like dependability, carbon emission reduction, diversification of energy sources, and reduction in power prices as seen by the consumer. The micro-grid approach focuses on utilizing locally available energy to meet the requirement of the society being served, like a town, university, business park, or shopping complex [2]. By smart micro-grids, the uses are many fold and extendable. One of the best use of smart micro-grid is it permits renewable resources on the community level [3].

Yet another advantage of smart Micro-grid is that, they are far better positioned than the centralized grid to satisfy the foreseen and unforeseen needs of the long term. Smart Micro-grid has the potential to extract the foremost from clean, renewable energy as a result of their adaptability to use a wider variety of energy sources [4].

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In sustainable power source, wind source has turned out to be a promising one. In WECS the turbine will constantly change its rotational speed as per wind speed. Amid high wind speed, variable speed wind turbine works in a better way to get most extreme productivity from wind [5]. The wind turbine is controlled to increase the productivity. The job of wind turbine control unit is to keep track of the rotor shaft speed and extracted power at required level. Unfortunately, because of the wild irregularity in wind speed and the huge size of wind turbine, it is hard to conduct study on it in a laboratory [6, 7].

In order to effectively utilize the wind resource and improve the performance of existing one, proper study of each and every component is essential. This paper introduces a unique experimental setup for conducting the study on different types of wind generators available in market. The different wind conditions and their effect on wind turbine can be emulated by separately excited DC motor. So once a wind resource assessment is made and a site is found to have the potential for harnessing wind energy a study can be conducted to select the type of generator best suited for the nature of wind prevailing in that terrain [1, 8].

This paper is organized as follows. The schematic diagram and its explanations are given in the second section. In this section the arrangement of the equipment's in the experimental setup are given. Simulation details and results are discussed in the third section. The experimental setup available in the lab is given in fourth section. Experimental results are presented in fifth section. A conclusion of the work done with future scope is provided in sixth section.

## 2. WIND TURBINE EMULATOR SETUP

In order to obtain an efficient wind energy conversion system, it is crucial to select its components wisely. The characteristics of motor selected should be in accordance with the wind turbine characteristics for the nature of wind in a given terrain. So it is best to emulate wind turbine for studying the characteristic of wind turbines under varying wind conditions and the nature of wind can be programmed as per requirement. Thus cost and space for wind turbine and its accessories can be eliminated [9].

### 2.1. Wind Turbine Emulator

The core module consist of ARM based processor (LPC2148 microcontrollers) board with keypad interface to provide inputs such as pitch angle, radius of the turbine, wind velocity, gear ratio and torque constant.

The Advanced RISC [Reduced Instruction Set Computing] Machine (ARM) based processor board is used for solving the differential equations in real time for emulating Wind turbine. It uses Pulse Width Modulator (PWM) port for power electronics converter/inverter firing. Two Analog to Digital Converter (ADC) channels are used to provide real time input such as motor speed and armature current. PWM pulses are provided for the DC-DC converter to drive the DC motor that emulates the wind turbine characteristics.

DC motor provides the torque for rotating the generator in contrast to conventional systems in which wind turbine rotates the generator. Torque speed characteristics of DC motor is controlled using armature voltage control that matches with wind turbine torque speed characteristics. Mechanical behavior of actual wind turbine is modelled in terms of linear differential equations. These equations are solved by numerical integration method in real time. In order to achieve fast calculation speed as generally required in real time simulations, ARM based processor based platform are chosen for solving the linear mathematical model of wind turbine. Armature voltage is controlled to develop the required motor torque for steady state operation [10].

User inputs the desired wind speed and pitch angle information. Turbine torque reference is calculated based on speed of the turbine and user inputted information. It is required that torque developed should be equal to this calculated torque. Since the motor torque is proportional to motor armature current, based on motor physical parameters, reference current is calculated. Reference current is compared with actual motor current and error is given to Proportional Integral (PI) controller which calculates the duty cycle for armature voltage control [11].

### 2.2 Wind Turbine Generators

There are four different types of generators which can be coupled to separately excited DC motor to configure as a Wind Turbine Generator set. The turbine and the generator are coupled using portable coupling as shown in Figure 1. The DC motor can be coupled to any one of the four type of generator at a time. The types of machines with their specifications are listed in Table 1.The Generators used to study the feasibility for WECS are:

a) Slip Ring Induction Generator (SRIG)
b) Squirrel Cage Induction Generator (SCIG)
c) Permanent Magnet Synchronous Generator (PMSG)
d) Permanent Magnet DC Generator (PMDC)

In a squirrel cage induction generator the winding is excited using capacitor bank. This provides the necessary reactive power support to the machine, while working without the grid supply. As there is no reference frequency the generated power will have variable frequency and voltages, as the prime mover torque vary. Hence the generated power is converted to DC using uncontrolled bridge rectifier. In order to make the DC voltages compactable a DC to DC converter is used. This procedure is followed for all the generated voltages by different machines, before giving to hybrid inverter.

In slip ring induction generator also the winding is excited using capacitor bank. When induction generators are connected to stable three phase supply, both the frequency and the terminal voltage of generated power are held constant by the supply. The same is not the case with Self Excited Induction Generator (SEIG), for which they vary with load even when the rotor speed is maintained constant. It may result in excessive voltage, current and increase in frequency. Even though the SRIG is more expensive and needs more maintenance, it allows slip-power control when driven by a variable-speed turbine. Another advantageous feature of the self-excited SRIG is that the rating of the rotor power is slip times low when compared with system rating [8, 10]. For this back to back converter is used in the rotor circuit. It is a three phase, 415V, 30A, Insulated Gate Bipolar Transistor (IGBT) based fully controlled bridge converter (SEMIKRON Module) [12-14].

The PMSG machine is a three phase machine capable of generating power output even at low speed. Also, it is capable of generation at variable speed [15, 16]. The Specifications of Wind Turbine Generators and Machines are shown in Table 1.

***Table 1****. Specifications of wind turbine generators and machines*

| S. No | Machine Type with Specifications |
|---|---|
| 1 | Alternator<br>1KVA, 3Ph, 415V, 50Hz, 1500rpm |
| 2 | DC Motor<br>1.5kw, 220V, 1500rpm |
| 3 | Squirrel Cage Induction Machine<br>1HP, 3Ph, 415V, 50Hz, 6pole |
| 4 | Slip Ring Induction Machine<br>2HP, 3Ph, 415V, 50HZ, 6pole |
| 5 | Permanent Magnet DC Machine<br>1Kw, 120V, 500rpm |
| 6 | Permanent Magnet Synchronous Machine<br>1kw, 3Ph, 200V, 500rpm |
| 7 | Mechanical Coupling Frame with anti-Vibration pad for Coupling DC motor with various other machine/generators |

The PMDC generator is capable of generating power at variable speed inputs. It also generates at low wind speed. Since the generated voltage is DC it can be converted to AC through an inverter. In order to make the DC voltages compactable for producing 440V AC supply, the input DC voltage is level shifted using a DC to DC converter [17, 18].

## 2.3 Alternator

An alternator is used to provide the reference sine wave for the inverter in the grid connected mode. The alternator is run by another DC motor, which have independent DC drive to control its operation. This arrangement helps in studying the effect of penetration of renewable energy on the conventional generation on a small scale prototype model. The alternator is protected by directional relay.

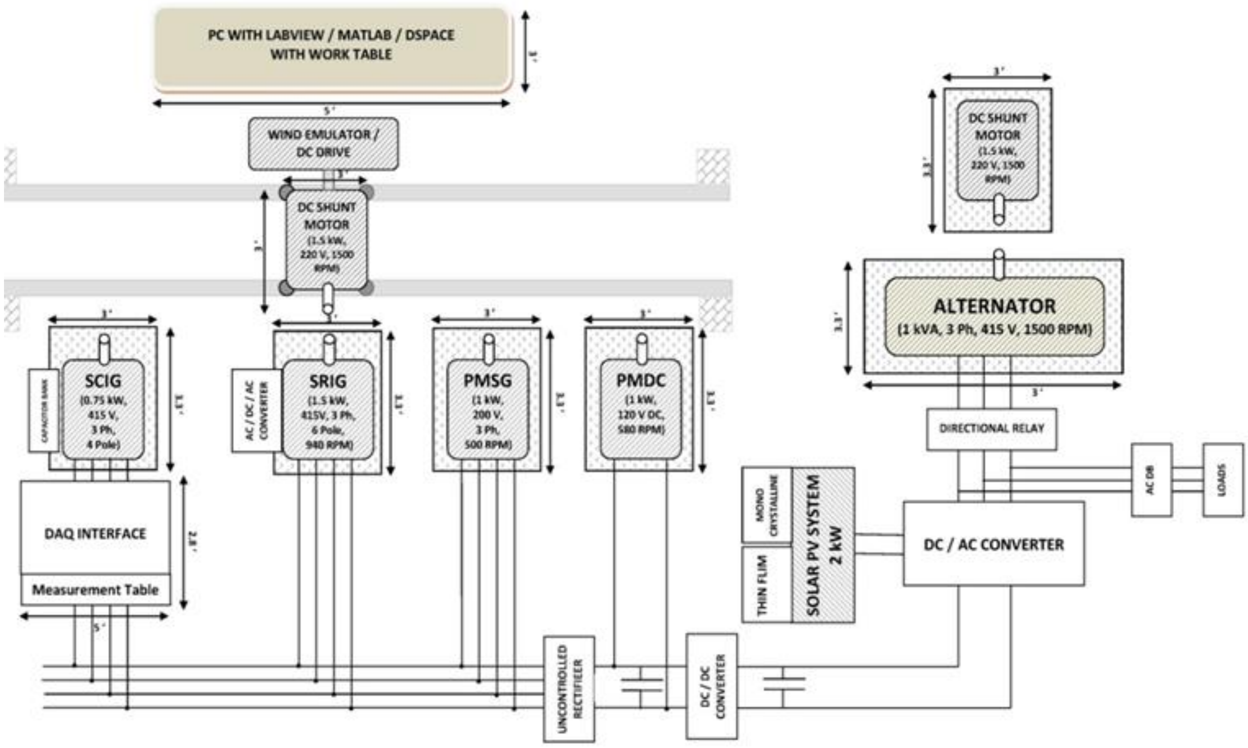


***Figure 1.*** *Schematic diagram of wind emulator setup*

## 2.4 Hybrid Inverter

For Power Conditioning and Grid Interface an Out back Inverter (FX2348ET (50Hz)) is used. It is rated for 2.3kVA, 230V, single phase AC supply. It requires 48V DC input. This is a hybrid inverter which can work in grid connected mode or stand-alone mode with the help of battery.

The output of generator is converted to DC using an uncontrolled rectifier and then using a DC-DC converter is given to the inverter. In the lab provisions are made to bring the DC output of mono-crystalline solar PV panels and thin film panels to the inverter [12].

An armature controlled separately-excited DC motor emulates the wind turbine characteristic. By means of controlling the chopper duty cycle the armature voltage applied to the motor is varied so as to imitate the wind turbine characteristic. There are two options available for controlling the duty cycle first by means of MATLAB/SIMULINK model of emulator interfaced with the help of Real Time Input Output (RTIO) Card to the external circuit. The second one is to generate the pulses externally by ARM based processor, which is explained in detail at the beginning of this section [5].

### 2.5 LabVIEW based Monitoring and Control of the Experimental Setup

The system consists of energy management unit, power generation and conditioning unit. A LabVIEW based Monitoring and Control of the Experimental Setup has been developed. Data Acquisition Cards (DAQ) is utilized to acquire various parameters such as speed, voltage, and current that are needed for control and monitoring of the system.

The Intelligence for the microgrid is created using LabVIEW based data logging and main control system (central controller). The inverter output is taken through NI DAQ (NI DAQ 9201) cards. The main controller will monitor and control the load management utilizing the data logging module [19].

### 2.6 DAQ Interface

The main use of a DAQ (Data Acquisition) system is to measure real world parameters. A DAQ system basically has five components to be considered. They are transducers for sensing the parameters, signal conditioners for signals processing and conversion. The accuracy of a DAQ system to measure different physical parameter depends on the ability of transducers to convert the physical parameter into electrical signals measurable by the DAQ hardware. Signal conditioning is done to improve accuracy, amplify the signal, provide isolation, filter out the distortions, and so on. It is essential to pick the proper hardware for signal conditioning.

Before the usage of a data acquisition board, it should be verified that the software can communicate with the board by way of configuring the devices. Measurement & Automation Explorer (MAX) configuration utility package of LabVIEW establishes connection with all device and channel configuration parameters [19].

### 2.7 Control Based on MATLAB with dSPACE

Model based approach makes it possible to test the control concept with ease, from the initial design using block diagrams to final online optimizations of the controller in real time. The microgrid main controller is developed to obtain a stable voltage and frequency. This is achieved using droop control, which is a well-defined control method widely available in literature. Microgrids based on droop control can achieve automatically adjustable voltage and frequency, without the aid of communication, which in turn improve system reliability. dSPACE, can be used for real time interfacing of the control strategy to validate the control technique [5].

The DS1104 R&D Controller is used which is a real time hardware based technology. The controller board is an ideal solution for controller's development and is widely used in various fields. The DS1104 R&D Controller board upgrades the PC to a powerful development system for rapid control prototyping. Real time interfacing RTI provides interfacing between Simulink blocks and the controller. RTI assures the implementation process, it also take care of change in variables over the run [20, 21].

## 3. SIMULATION OF WIND TURBINE GENERATOR

Figure 2 shows the simulation block diagram of Wind Turbine Emulator. It mainly contains a wind turbine model, an IGBT based chopper, a separately excited DC motor, and SEIG.

A wind turbine model is used to compare the output of separately excited DC motor working as wind turbine emulator and the turbine model. Steady state power equations are used for modeling the turbine. The drive train stiffness is taken as infinity. The generator to which the turbine is coupled includes the inertia and friction factor of the turbine. The output power equation of the turbine is given by Equation (1)

$$P_m = \frac{C_p(\lambda,\beta)\rho A v^3}{2} \qquad (1)$$

Where $P_m$ = Mechanical Power output of the turbine (W),$C_p$ = Performance coefficient of turbine ,ρ = Air density (kg/m$^3$),A = Turbine swept area (m$^2$) ,v = Wind speed (m/s),λ = Tip speed ratio of the rotor blade to wind speed ,β = Blade pitch angle (deg). A generic equation is used to model Performance coefficient of turbine $C_p$ (λ, β). The turbine characteristic is given by Equation

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{C_5\lambda_i} + C_6\lambda, \tag{2}$$

Where, $$\frac{1}{\lambda i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

The power coefficient $C_p$ is a non-linear function of tip speed ratio and pitch angle, which is to be specified for each type of turbine. Every turbine manufacturer provides look up tables for $C_p$. Apart from those given by manufacturers; models for power coefficient have been developed. According to one such model commonly used the values of the coefficients $C_1$ –$C_6$ are taken as $C_1$ = 0.5176, $C_2$ = 116, $C_3$ = 0.4, $C_4$ = 5, $C_5$ = 21 and $C_6$ = 0.0068.

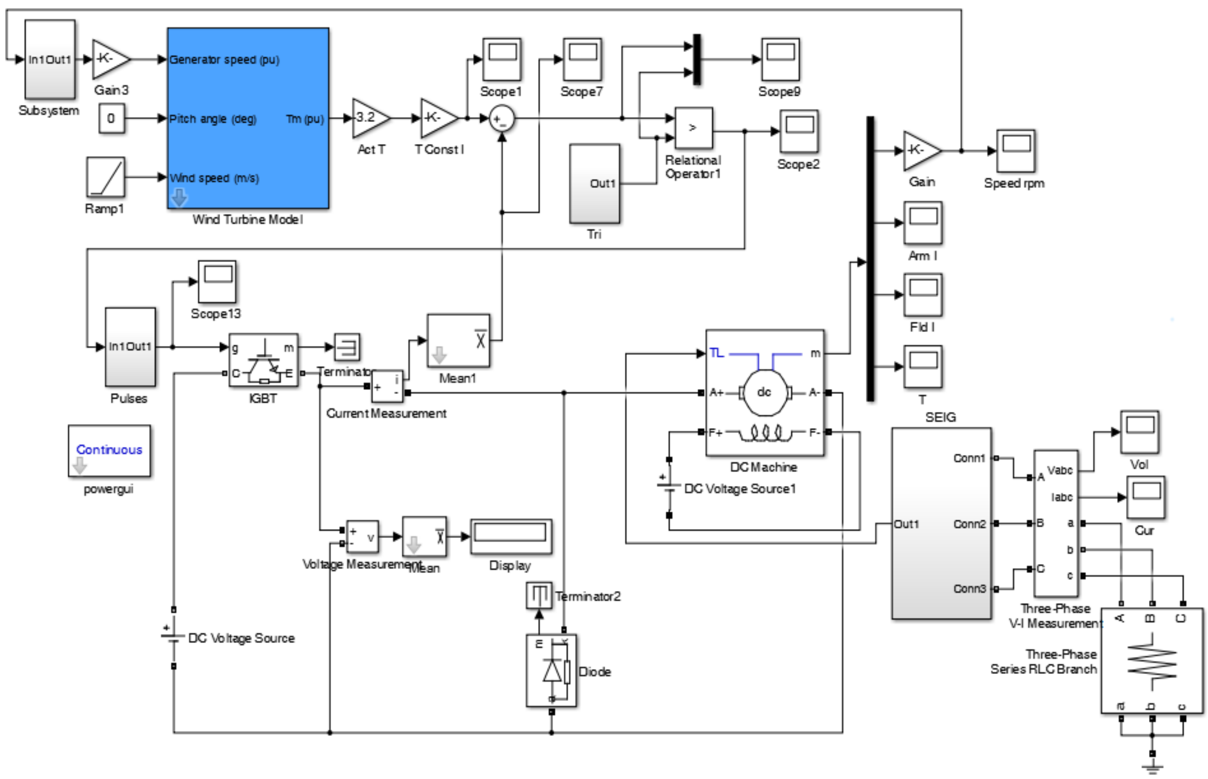


***Figure 2.*** *Simulink block diagram of wind turbine emulator with SEIG*

Equation 2 is utilized to simulate emulator model, turbine model and to obtain the turbine power characteristics. Figure 3 shows the turbine power characteristic for the above developed wind turbine model with base speed of 8 m/s. This figure also gives family of power curve for different wind velocity. As the wind speed increases the power produced increases but efficiency of power conversion will be maximum for designed base wind speed [22].

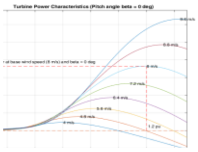

***Figure 3.*** *Turbine power characteristic for different wind velocity with 8m/s as the base wind speed*

In the wind turbine emulator, the torque output of turbine block is compared with motor torque. The reference torque required is obtained from wind turbine model block. The torque output of turbine model is converted to equivalent current for separately excited DC motor, which is taken as the reference current. The separately excited DC motor actual current is compared with the reference current. The armature voltage is controlled using a chopper to produce current equal to the reference current. The chopper duty cycle is controlled by the error in current comparator. The actual current and reference current values are shown in Figure 4. For study of turbine torque a ramp input is given as the wind velocity. As it can be seen from Figure 4 the reference current is changing according to wind velocity and motor current is trying to follow it.

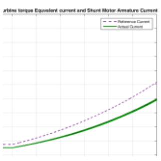

***Figure 4.*** *Comparison of turbine reference current and actual motor current*

Figure 5 shows the Simulink block diagram for the SEIG subsystem. The SEIG subsystem consists of a squirrel cage induction machine, which is self-excited by an initially charged delta connected capacitor bank.

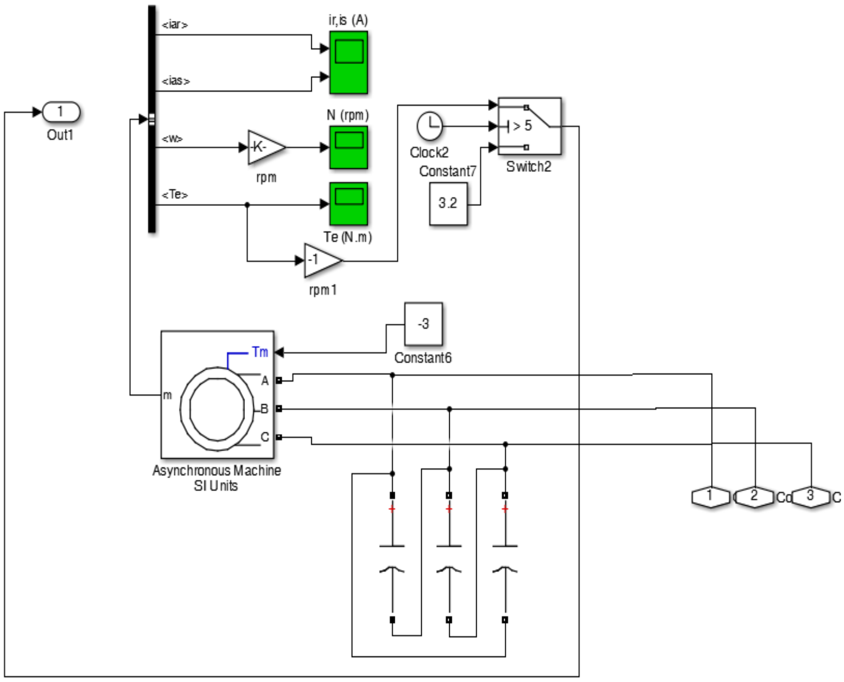


***Figure 5.*** *Simulink block diagram for SEIG subsystem*

The generator is loaded with resistive load at full load capacity of generator and the load torque generated is given as load torque for motor. The generated three phase voltage across the resistive load is shown in Figure 6.

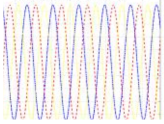

***Figure 6.*** *Generated three phase voltage across self -excited squirrel cage induction generator*

As there is some initial transients at the generator side as well as the motor side some switching arrangements are done which will ensure connection of these two units only after they attain stable operating condition.

## 4. IMPLEMENTATION AND WORKING OF THE HARDWARE MODULE

Figure 7 shows the experimental setup for emulating the wind turbine characteristics which primarily consists of a separately excited DC motor with four types of generators that can be coupled one at a time.

The machine numbered 1 is a separately excited DC motor, 2 is SCIG, 3 is SRIG, 4 is PMDC, and 5 is PMDC. Figure 8 shows the overall machine arrangement along with alternator and DC motor set numbered as 6 and 7. All the machine terminals are brought to a terminal board for ease of taking measurements. The terminal board is shown in Figure 9. Two DC drives are available on the panel board to drive the two separately excited DC motors.

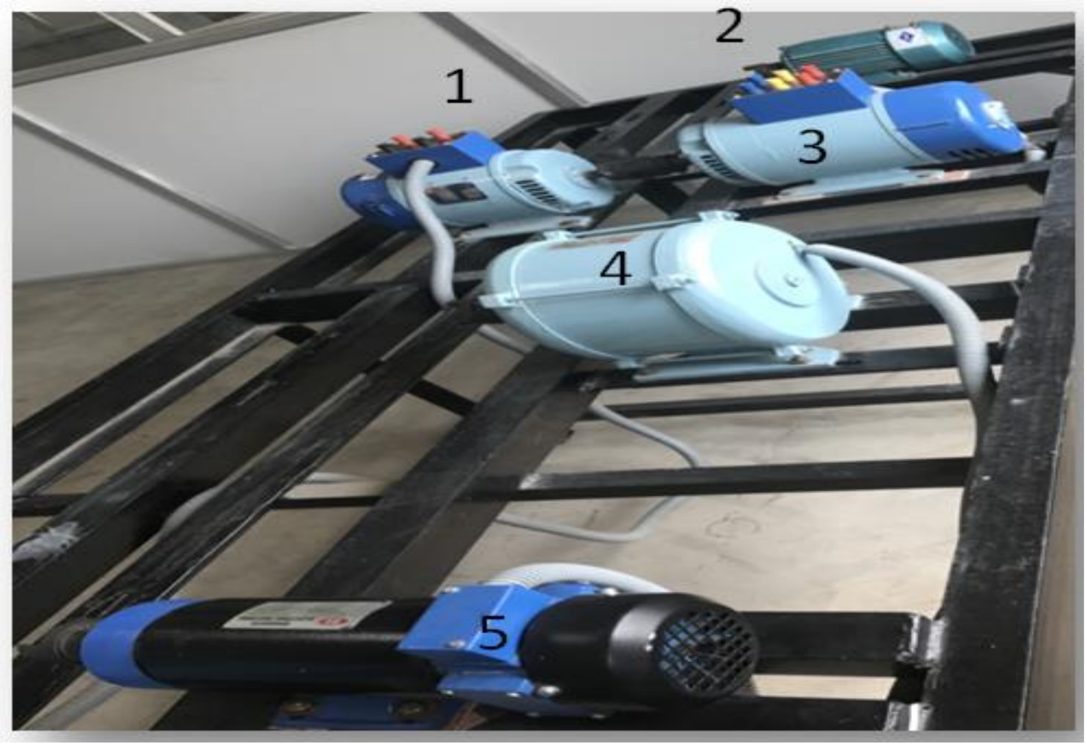


***Figure 7.*** *DC motor and four different types of generators*

The first DC drive is for driving the motor alternator set which generates the grid reference sine wave for the hybrid inverter. The second DC drive is for wind turbine emulator. Apart from machine terminals the panel board consists of two digital voltmeters, two digital ammeters and a multi-function meter for taking the measurement. All the meters available on the board can be used for taking measurement independently as per requirement.


***Figure 8.*** *Overall machine arrangement along with alternator motor set*


***Figure 9.*** *The terminal board*

The generator under study is coupled to DC motor and supply is given to the motor. Once the Motor Generator (MG) set attains the rated speed and rated voltage is generated the load is applied gradually to the generator. The machine is loaded till the rated capacity of the motor.

## 5. PERFORMANCE CHARACTERISTICS OF VARIOUS WIND TURBINE GENERATORS UNDER LOADED CONDITION

The performance characteristic of all the machines is given in this section.

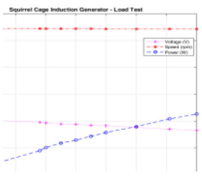


***Figure 10.*** *Performance characteristics of SCIG*

Figure 10 gives the performance characteristic of SCIG excited by capacitor bank. As it can be seen from the plot the generator is having a good voltage regulation.

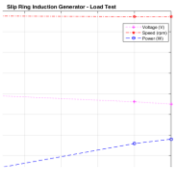


***Figure 11.*** *Performance characteristics of SRIG*

Figure 11 gives the performance characteristic of SRIG excited by capacitor bank. As it can be seen from the plot the generator is having good regulation but couldn't be loaded enough due to overloading on motor side.

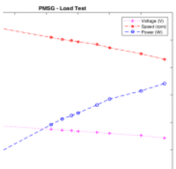


***Figure 12.*** *Performance characteristics of PMSG*

Figure 12 shows the performance characteristic of PMSG. From the plot it is clear that for low speed appreciable voltage is generated and power can be extracted efficiently.

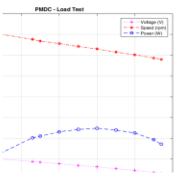


***Figure 13.*** *Performance characteristics of PMDC*

Figure 13 shows the performance characteristic of PMDC. From the plot it is clear that similar to PMSG for low speed appreciable voltage is generated and power can be extracted efficiently even at low wind speed.

## 6. CONCLUSION AND FUTURE SCOPE

It is troublesome to wait for appropriate wind conditions to make a study so as to come to a conclusion in order to select the best type of generator. Moreover an actual wind turbine is costly to procure and bulky to install for study purpose, when compared to equivalent DC motor which can be used to emulate the same. It is validated with simulation and experimental results that, an armature voltage controlled DC motor can be effectively used to emulate the wind turbine. So such an experimental setup will help to promote the growth of wind energy generation by making the studies easier. The generators under study are undergoing actual torque variations as in the case with real field conditions.

A unique experimental setup for the study of machine performance for checking the feasibility of a generator for wind energy conversion system is presented in this paper. Normally what is seen in the literature survey is a motor generator set wherein the motor will be controlled so as to emulate the turbine characteristic and will be permanently coupled to any one type of generator. Over here a portable coupling is made by which four different types of generators which are more commonly used in the field can be studied which will give a more realistic and ideal platform for comparison. The comparison is done on common ground (as the emulator is same) and under almost real field conditions. As can be seen from the plot, for fixed wind speed conditions SCIG and SRIG are a better option but for low and varying wind speed condition the PMSG and PMDC are a better option.

The experimental study can be extended by comparing the results of machine performance with the closed loop control of wind emulator setup. For wind emulator setup two options are available in the lab, one based on ARM processor and other based on MATLAB model interfaced with RTIO card. Hence the performance of the above mentioned options can be compared, and commented.

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## CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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