An Investigation of Power Performance of Small Grid Connected Wind Turbines Under Variable Electrical Loads

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Abstract

In this study, the power performance of two small grid connected wind turbines has been investigated. The objective was to study the impact of load power factor on the wind turbine power curve. Two small wind turbines were tested in a number of load conditions and test data were collected for approximately two months. A set of resistors, inductors and capacitors were used as load in addition to the grid connection. One second data was collected for at least two days in each load condition. Data was analysed for active power, power factor and reactive power. Wind turbines' power curves are plotted with load and without any load connected between the wind turbine and the grid. Results indicate that the type of load does not significantly affect the power curve of a small wind turbine. It was also observed that above 15% of rated power, the power factor of a small grid connected wind turbine was also constant.

Keywords

Small wind turbine power performance; grid connected small wind turbine; wind turbine under variable electrical loads; reactive power of small wind turbine; power factor of small wind turbine

Introduction

The wind industry has been contributing a significant percentage of electric power generation all over the world. The power performance and power quality of wind turbines and their interaction with the grid is becoming an important issue [1]. Small wind turbines are being widely used to fulfil local demands. They are used for dairy farms, water supplies for small communities, small industry, irrigation and greenhouses. Many of these turbines are grid connected, so when there is excess electricity they can store the extra power to a grid and when there is a lack of electric power from the wind turbine, they can use from the grid in the case of net metering.

To produce electric energy, doubly-fed induction generators (DFIG) in large wind turbines and permanent magnet generators (PMG) in small wind turbines have been widely used. Since a PMG has its own permanent magnet, it does not require an external excitation current and it does not consume reactive power from the grid. PMGs are dominant in small wind turbine systems because of higher efficiency and small size compare to DFIG system [2].

Power performance for small wind turbines is very important. The manufacturers provide a power curve for their wind turbines, which is essentially turbine-produced active power versus wind speed. Depending upon the situation, the small wind turbine load may be resistive, inductive or sometimes capacitive in nature. As the small wind turbines are in dispersed locations, they could be used to provide local reactive power consumption. That may decrease the reactive power flow and also decrease the overall power losses [3].

In this article, the power performance of small wind turbines has been investigated. Two wind turbines were tested at the Wind Energy Institute of Canada (WEICan) with a resistive, inductive and capacitive load. Recorded data has been compared and analysed for active power, reactive power and power factor. The results and discussion are presented below.

Grid Connected Small Wind Turbines

Most small wind turbine systems consist of a rotor, generator, rectifier and inverter. After an inverter, the system is connected to an AC panel; the local load is also connected to an AC panel. Before connection to the grid, typically, power goes through a transformer to change the voltage level. For our experiment, the system was arranged in a similar way. To convert the wind energy into mechanical energy, a wind rotor is used. Most of the commercially available small wind turbines use furling, flapping, passive pitching and soft stall for their over speed and power control capacity [4]. For electric power generation, various types of generators have been used. Among them, a permanent magnet generator is widely used. As the wind speed and wind direction change every second, so does the total extracted power. As a result, the produced electric power from the generator is not uniform. The AC power from the generator is first converted to DC power with the help of a rectifier. Then, the DC power is again converted to the desired AC power so that the output can be connected with grid. The inverter plays a vital role in this system. The inverters must produce good quality sine-wave output and must follow the frequency and voltage of the grid. The inverter must observe the phase of the grid, and the inverter output must control voltage and frequency variations [5]. Most commercially available grid tie inverters have an active power factor controller to reduce the Total Harmonic Distortion (THD).

Experiments and Results

To investigate the power performance of small wind turbines, two different turbines were used. For our experiment, we can say that they are turbine A and turbine B. Normalized data will be used in his paper.

For data logging, a Campbell scientific 1000 data logger was used, collecting the data every second and storing it in a PC. This creates a file for the entire day (24 hours). Raw data (second data) is later converted to one minute average data. Then, one minute data was normalized and the power curve was plotted using the bins method [6]. The bins method was also used to compare the reactive power and power factor.

For the experiment with a motor, a second Hioki meter was used. It measured three phases - active power, power factor and reactive power - every second and stored the data in a memory card and the collected data was moved from the memory card to a PC.

Experiments with turbine A

Turbine 'A' is a PMG based small wind turbine and used stall regulation for its control system.

The specifications of this turbine are as follows:

- Power Regulation: Non-stop output control
- Permanent magnets generator (3 phase, synchronous)
- Over Speed Control/Protection: Stall Regulation
- Inverter output Voltage: 120V/208V
- Voltage Tolerance: ± 5%
- Grid Frequency: 60Hz
- Frequency Tolerance: ± 0.00083%

1) Power performance without any local load:

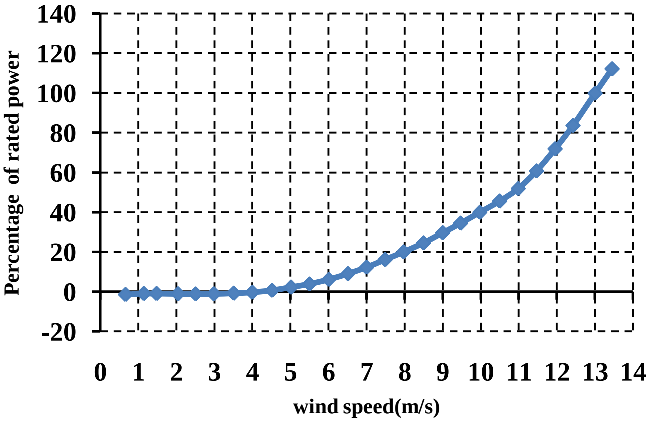
The turbine was grid connected. If any load was connected between the grid and turbine, in this article, it will be called local load. For comparison with local load and non-local load, the power performance data of the turbine with non-local load was collected for ten days. Then, one minute average values were calculated and normalized. Finally, by using the bins method, the power curve, reactive power curve and power factor curve were plotted.

Fig. 1(a) shows the power curve of the wind turbine A. In Fig 1(b), the power factor is plotted and it indicates that, when wind speed is more than 9 m/s, the power factor is close to unity.

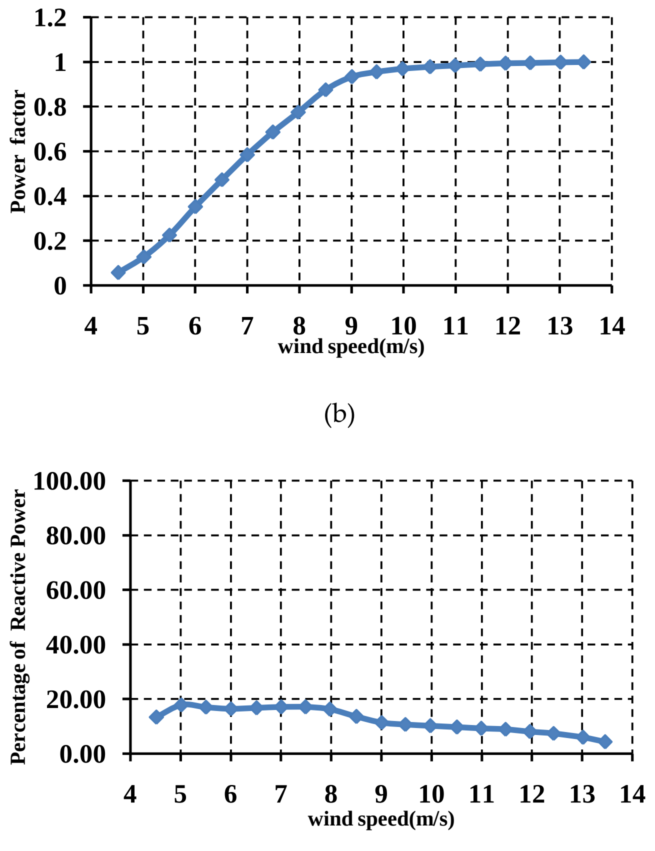
Power factor =active power/apparent power

Apparent power^2= active power^2+ reactive power^2

Reactive power is plotted in Fig 1(c) and it can be observed that reactive power is almost linear and it is less 20% of rated power.



(a)



(b)

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FIG. 1 POWER PERFORMANCE OF TURBINE A WITHOUT ANY LOCAL LOAD A) POWER CURVE, B) POWER FACTOR, C) REACTIVE POWER

Active power output depends on wind speed and it typically increases as the wind speed increases. But with wind speed increase, there is no significant change in reactive power compared to active power change. At high wind speeds, apparent power is almost equal to active power and thus the power factor improves at high wind speed.

2) *Experiment with Heaters (Resistive Load)*

To experiment on whether resistive load can have an effect on the power performance of wind turbines, three heaters with phase b and/or phase c were connected, as shown below in Fig. 2. It is noted that the turbine is connected to phase b and phase c of the transformer. The heaters were adjusted to maximum point. One of the heaters was a turbine shed heater. It was configured for 208 volt and it was connected to phase b and phase c. The other heaters were portable and were configured for 120V and they were connected to phase b-neutral and phase c-neutral. They were kept outside the shed to prevent over heating.

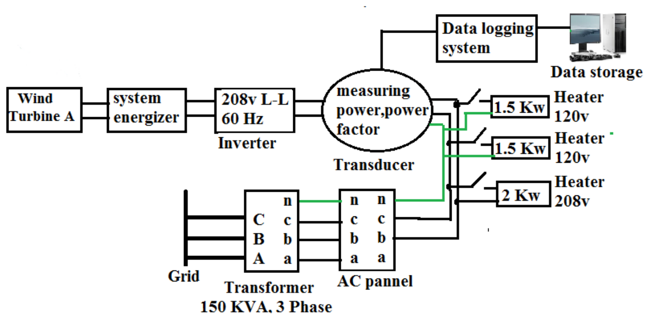
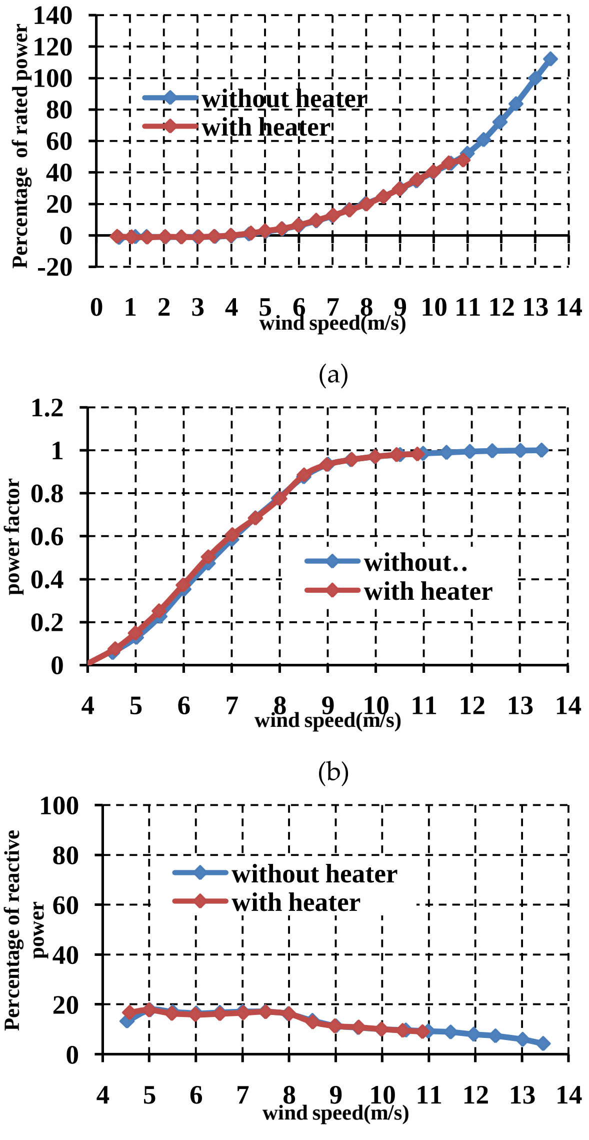


FIG. 2 BLOCK DIAGRAM FOR AN EXPERIMENTAL SETUP WITH RESISTIVE LOAD (HEATER)

Heaters were connected for 6 days and 1 second data was collected. Data was converted to 1 minute average data. Using the bins method, the power performance curves were plotted and these are shown in Fig. 3.



(a)

(b)

(c)

FIG. 3 POWER PERFORMANCE COMPARISON OF TURBINE A WITH RESISTIVE LOAD A) POWER CURVE, B) POWER FACTOR, C) REACTIVE POWER CURVE

From Fig. 3(a), it can be seen that there is no change in power curve. In Fig. 3(b), there is no change in power factor also. In both cases, when wind speed is greater than 9m/s power factor was very close to unity. Fig. 3(c) shows that there is no significant change in reactive power. In both cases, reactive power decreases gradually and it is always less than 20% of rated power. Therefore, we can say that there is no significant effect of heaters on the output power, power factor and reactive power.

3) Experiment with a 5hp induction motor:

For the experiment with inductive load, a 5hp induction motor was used as the load. The motor was connected before the transformer. The motor was in no load mode, so its active power consumption was low but reactive power was high. The motor was a three phase motor. The motor was left for three days and one second data was collected for those days. After that, a set of compensation capacitors was connected for two more days and one second data was collected again. Data was analysed using the procedure mentioned earlier.

In this case, second meter (Hioki meter) was connected before the transformer. This meter measured the whole building power performance for every second. Here, the whole building includes the wind turbine, inductive motor, data logger, and building lights. Data was analysed using the bins method. The connection diagram is below in Fig. 4 and data is plotted in Fig. 5.

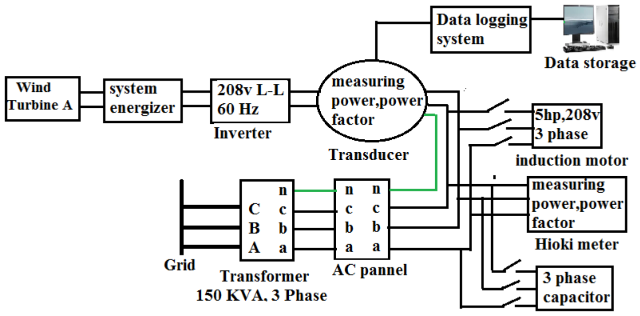


FIG. 4 BLOCK DIAGRAM FOR EXPERIMENTAL SETUP WITH AN INDUCTIVE LOAD (MOTOR) AND CAPACITOR

From Fig .5(b), we can find that, when the inductive load was connected, the whole building power factor was decreased and when compensation capacitors were connected, the power factor improved. Fig. 5(c) shows that the total demand of reactive power for the whole building was more than 145% of rated power, but with compensation capacitor it was similar to reactive power as without a motor.

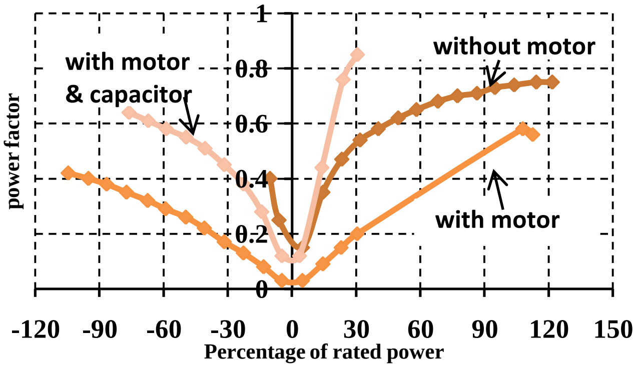


FIG. 5 (A) POWER FACTOR COMPARISON OF THE WHOLE BUILDING WITH INDUCTIVE AND CAPACITIVE LOAD

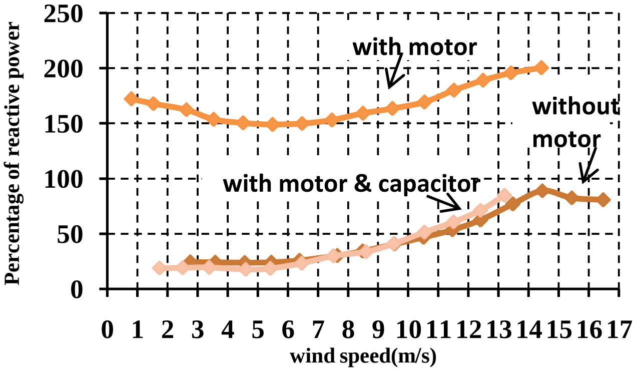
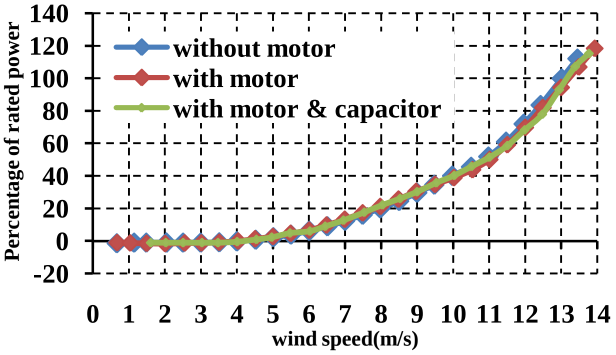


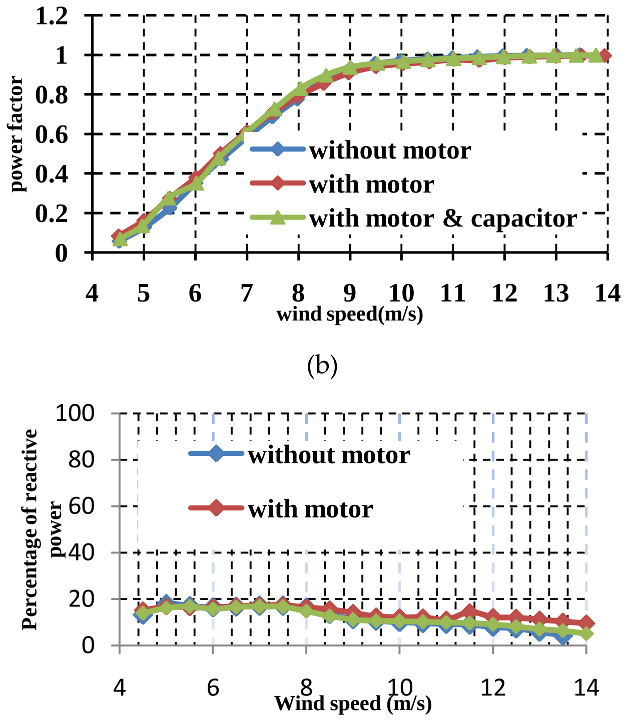
FIG. 5 (B) REACTIVE POWER COMPARISON OF THE WHOLE BUILDING WITH INDUCTIVE AND CAPACITIVE LOAD

Experimental result & comparison in the turbine transducer:

From Fig. 6(a) it can be observed that the power curve for all the three cases i.e. without motor, with motor and with motor & capacitor are about same. There is no effect of the induction motor and capacitor. Next, two curves indicate that the power factor is almost similar and reactive power is still less than 20% of rated power. So, the inductive load and compensation capacitor have no effect on the power performance of this small grid connected wind turbine.



(a)



(b)

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FIG. 6 POWER PERFORMANCE COMPARISON OF TURBINE A WITH INDUCTIVE AND CAPACITIVE LOAD A) POWER CURVE, B) POWER FACTOR, C) REACTIVE POWER

Experiments with Turbine B

Turbine B is also PMG based small wind turbine. It uses the furling method for its control system.

The specifications of this turbine are given here:

- Power Regulation: Active – Inverter
- Utility interconnection voltage and frequency trip limits and trip times: Programmable, Utility specific
- Total Harmonic Distortion (current): < 3%
- Trip limit and trip time accuracy:<10%
- Grid Voltage: Single phase, 208V
- Tolerance: ± 5%
- Grid Frequency: 60Hz
- Tolerance: ± 0.00083%

1) *Power performance without any local load:*

Fig. 7 below shows the turbine power curve generated from the data collected over a number of days. It indicates that wind turbine B has a nonlinear power curve and it is not consistent. Sometimes, it goes into stall regulation too early, say at 8m/s or 10 m/s and remains stalled above that wind speed; which is due to furling control system. At that time, it does not produce any power. The following three power curves are for the same conditions (i.e. without any local load, turbine is connected to the grid directly).

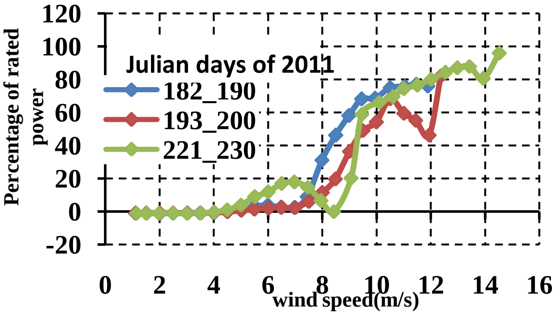
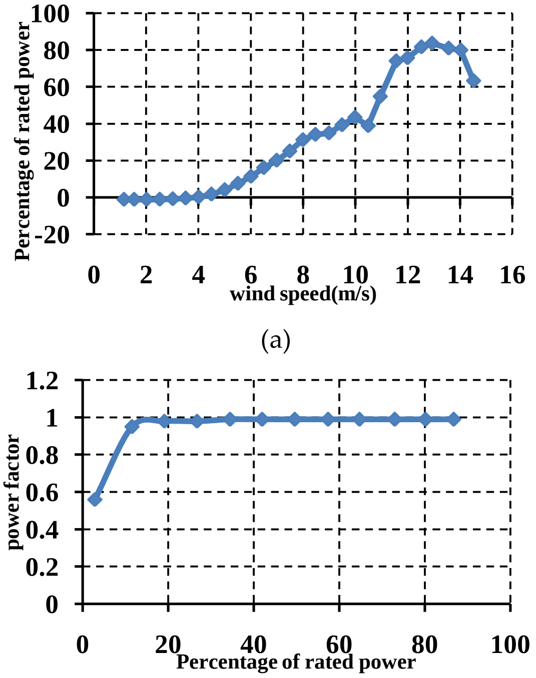


FIG. 7 POWER CURVE VARIATION FOR TURBINE B UNDER THE SAME CONDITIONS

Therefore, it is very difficult to compare power curves with and without local load.

For our experimental comparison, one second data for fourteen days without any local load was collected and plotted following the same procedure as described above for wind turbine A. The power curve and reactive power against wind speed was plotted. As the active power varies for the same wind speed, here we have plotted the power factor against the active power instead of power factor versus wind speed.

Fig. 8 shows that the power factor is very constant. When output power is more than 15% of rated power, the power factor becomes unity. Reactive power is always less than 15% of rated power



(a)

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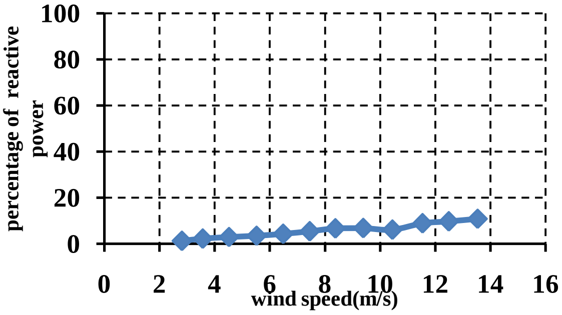

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FIG. 8 POWER PERFORMANCE OF TURBINE B WITHOUT ANY LOCAL LOAD A) POWER CURVE, B) POWER FACTOR, C) REACTIVE POWER

2) *Experiment with Heaters*

Experiments were repeated similar to wind turbine A for resistive load. Turbine B was connected to phase A and phase B in the AC panel, so all the heaters were connected to phase A and/or Phase B, as shown in Fig. 9 and data was collected and analysed. Recorded data is plotted in Fig. 10.

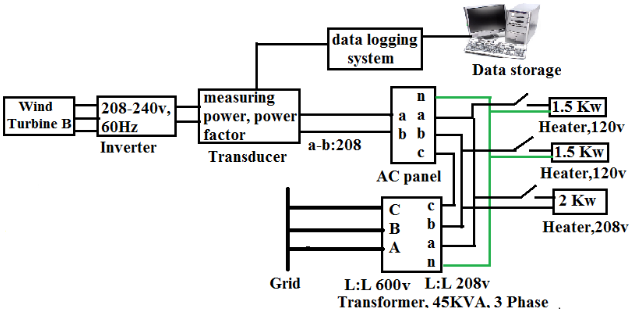
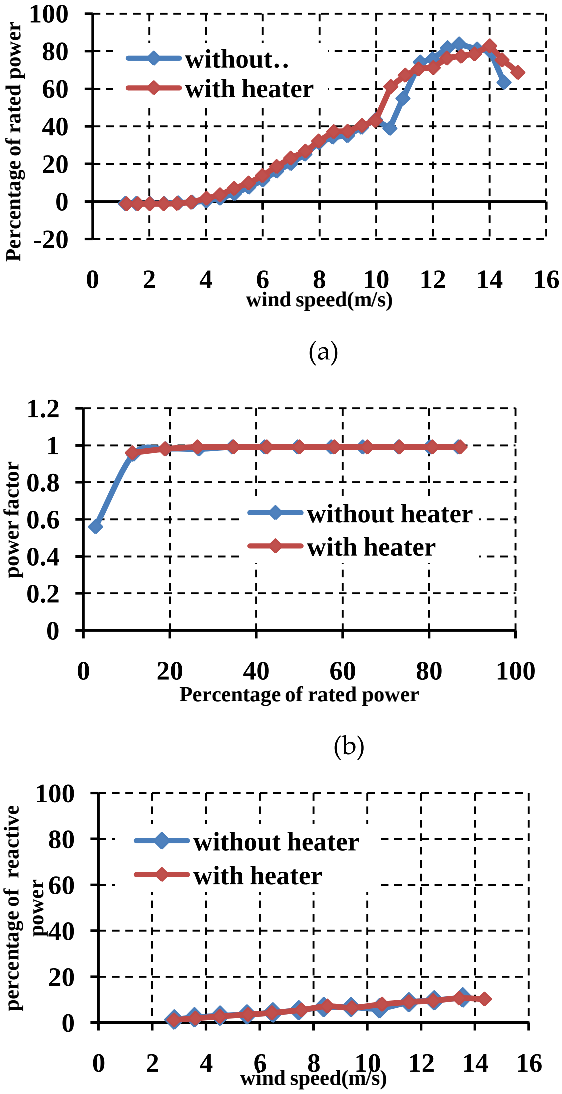


FIG. 9 BLOCK DIAGRAM FOR EXPERIMENT SETUP WITH RESISTIVE LOAD (HEATER) FOR TURBINE B

From Fig. 10(a) we can see that there is a little change in the power curve. As mentioned earlier, the power curve is not constant for this wind turbine, so it is better to look at the power factor and reactive power. The power factor is also unchanged. From Fig. 10(b), for both cases, the power factor was close to one when active power was greater than 15% of rated power. Fig. 10(c) also shows that there is no significant change in reactive power. In both cases, reactive power increases gradually and it was always less than 15% of rate power. Therefore, it could be concluded that there is no significant effect of resistive load on the power performance of turbine B.

3) *Experiment with 5hp induction motor and capacitors:*

The experiment was repeated for turbine B with inductive and capacitive load. Fig. 11 shows connection diagram for this set of experiments. As



(a)

(b)

(c)

FIG. 10 POWER PERFORMANCE COMPARISON OF TURBINE B WITH RESISTIVE LOAD A) POWER CURVE, B) POWER FACTOR, C) REACTIVE POWER

mentioned earlier, a Hioki meter was used before the transformer to measure the whole building power performance. Collected data was analysed and it is plotted in Fig. 12.

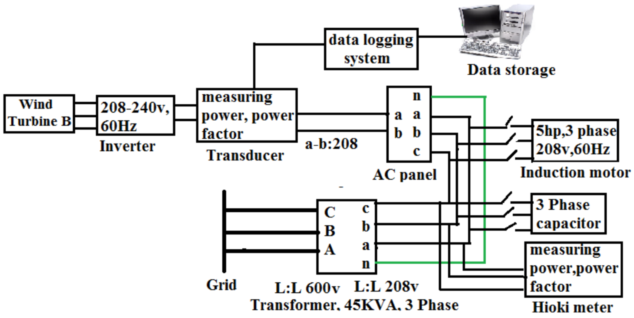


FIG. 11 BLOCK DIAGRAM FOR THE EXPERIMENTAL SETUP WITH AN INDUCTIVE LOAD (MOTOR) AND CAPACITOR FOR TURBINE B

Experimental result & comparison in the Hioki meter:

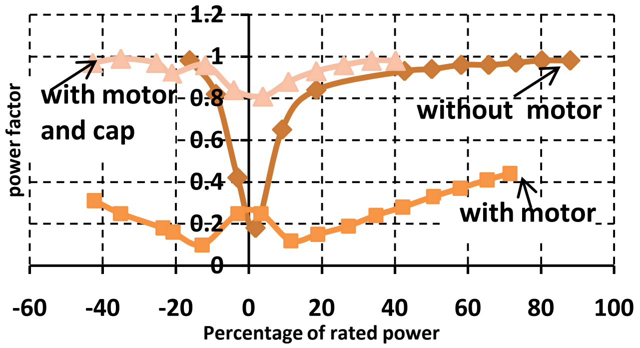


FIG. 12 (A) POWER FACTOR COMPARISON OF THE WHOLE BUILDING WITH INDUCTIVE AND CAPACITIVE LOAD CONNECTED TO TURBINE B

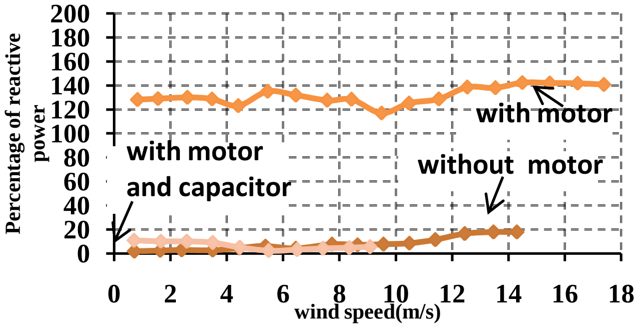


FIG. 12 (B) REACTIVE POWER COMPARISON OF THE WHOLE BUILDING WITH INDUCTIVE AND CAPACITIVE LOAD CONNECTED TO TURBINE B

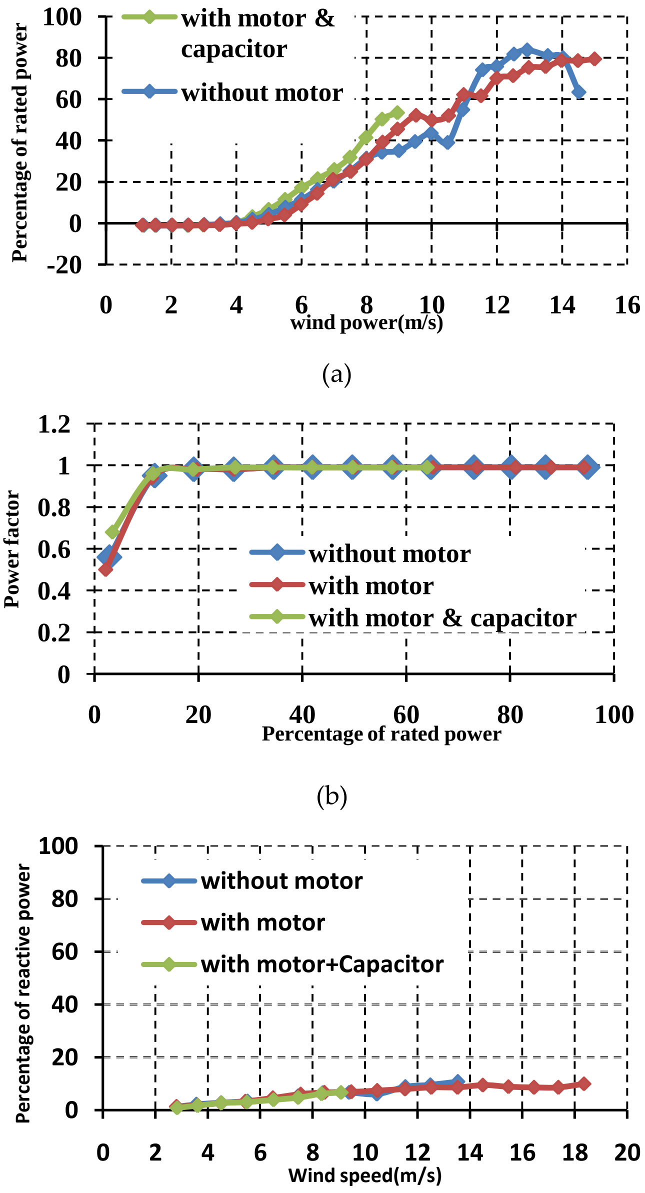
In Fig. 12(a), we can see that, when active power is greater than 15% of rated power in both directions (from grid or to grid), the power factor is very close to unity without the motor. When we connected the motor, power factor decreased, but when compensation capacitors were added, the power factor improved and came back to unity.

From Fig. 12(b), without the motor reactive power is more or less 20% of rated power. But when the motor was connected, the whole building demand for reactive power increased and it was greater than 120% of rated power. After that, capacitors were connected and the reactive power demand for the whole building was decreased.

More test results are presented in Fig. 14. Turbine transducer data was collected and analysed as described previously for turbine A.

Experimental result and comparison in the turbine transducer:

From the plots in Fig. 14(a), we can see that the power curve varied slightly. As this turbine power curve is not a constant, it is better to compare the power factor and reactive power. From Fig. 14(b) and Fig. 14(c), it can be seen that there is no significant effect of the inductive load and compensation capacitor on the turbine power factor and reactive power.



(c)

FIG. 14 POWER PERFORMANCE COMPARISON OF TURBINE B WITH INDUCTIVE AND CAPACITIVE LOAD A) POWER CURVE, B) POWER FACTOR, C) REACTIVE POWER

Conclusions

This paper described the power performance of two small wind turbines under variable load conditions. The active power performance, the power factor condition and the reactive power performance under resistive load, inductive load and compensation capacitor load have been presented in this paper. From the data, it is concluded that there is no significant effect of load type on the power performance of a small grid connected turbine. When experiments were done with a 5hp inductive motor, which consumes reactive power more than 120% of rated power, it was found that the turbine also had no effect on its reactive power production; thus, the power factor remained unchanged. The motor consumed the reactive power from the grid. Therefore, these experimental results show that the small wind turbine cannot produce any reactive power for induction or capacitive load. The wind turbine inverter basically acts as a current source and its current phase angle is very close to the grid voltage phase angle.

Most of the small wind turbines are situated in remote locations isolated from the national power plant. If someone buys a small wind turbine to run a small motor for his/her business and connects the turbine to the grid, then the system will still consume reactive power from the grid and there could be loss or utility penalty for the reactive power. A control system should be developed so the owner can adjust the reactive power and power factor for an optimal operation and minimal reactive power from the grid.

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