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Performance improvement in an Indian wind farm by implementing design modifications in yaw and hub hydraulic systems—A case study

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ABSTRACT

In India, wind power has emerged as the leading green energy technology with an average growth rate of 30%. Wind power has been concentrated in few regions especially the southern state of Tamil Nadu, which maintains its position as the state with the largest wind power installation. Due to the rapid growth of wind farms, the technical availability and the performance issues are to be studied in detail in specific locations where the wind is turbulent in nature. As most of the European wind turbine designs are facing critical problems in Indian atmosphere, detailed study in the individual wind farms is required to increase their performance. Hence rather than the technical advancements of wind turbine generator (WTG), certain measures to enhance the power production in the existing wind farms are essential. This paper deals with two critical issues and suitable remedial measures in an existing wind farm. The proposed designs are implemented and tested in the wind farm. The performance analysis is made for two years duration before and after installation. It is observed that the effectiveness of the yaw system and hub hydraulics was enhanced.

Contents

1. Introduction

Growing demand on power needs is gradually gaining interest on developing wind energy conversion systems as a suitable source of renewable energy. The economical and environmental factors also contribute to the research and development on

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exploring various means of increasing the performance of wind turbine generators. The majority of the commercial wind energy conversion systems in India are equipped with horizontal axis, upwind configured wind turbine generators (WTG) due to their various advantages.

In the last decade, the average annual growth of installed wind farm capacity in the world is around 30%. Harnessing of wind energy could play a significant role in the energy mix of each nation [1,2]. The sun radiates 1 PW or 1014 kW h, of energy every hour; as little as 3% of this if being converted into wind energy, will be able to meet the global power demand today. It is estimated that about 10^6–10^7 MW of usable power is continuously available in the earth′s winds. The magnitude of this vast potential is in striking contrast with that of the hydro power potential of the earth. As per projections made by the Global Wind Energy Council, the present installed capacity is 158.5 GW. The size of the global annual wind market is expected to reach 62.5 GW by 2014 and the cumulative capacity by 2014 would be around 409 GW.

There are three basic designs of large and medium wind turbine generators that are operational around the world. The basic type is a gear driven fixed speed wind turbine driving a squirrel cage induction generator connected to the grid. The next type is variable speed wind turbine employing gear mechanisms and doubly-fed induction generator with required power electronics interface. The third one is direct driven wind turbine employing synchronous generators controlled by power electronic converters [1,3–5].

India, being an important player in wind power development is actively contributing in harnessing wind energy for electrical power extraction. It is the fifth largest producer of wind power after China, USA, Germany and Spain with a total installed capacity of 18.421 GW as of December 2012. They employ grid connected induction generators which convert wind energy to electrical energy to be fed to the grid [6].

As the concentration of WTG is more in Kanyakumari district of Tamil Nadu, India, the performance issues play a vital role. This paper aims on analyzing the performance measures of a wind farm located in this area and the reasons for low power production in a group of wind turbine generators compared to the neighboring machines. A novel strategy to improve the production by modifying the existing design in the yaw system is proposed, implemented and analyzed for a significant period of time. The results obtained are encouraging in terms of power production when compared with the neighboring machines and the previous year′s performance. There are thousands of similar group of wind turbine generators in this turbulent windy area. Hence the proposed design may be applicable to those wind turbine generators. Commercially most of the other wind farms are also installing the proposed designs to increase the power production.

2. Wind power in India

In India, wind power is at the threshold of a new era. The wind power programme in the country was initiated towards the end of the sixth plan, in 1983–1984. A market-oriented strategy was adopted from inception, which has led to the successful commercial development of the technology. The Indian wind energy sector has shown impressive growth in the past few years and investments into the sector have increased significantly. The total potential for wind power in India was first estimated by the Centre for Wind Energy Technology (C-WET) at around 45 GW and was recently increased to 48.5 GW, which is presently adopted by the Government as the official estimate.

Wind in India is influenced by the strong south-west summer monsoon, which starts in May–June, when humid air moves towards

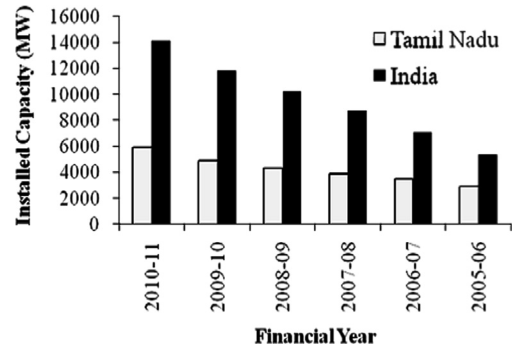

Fig. 1. Development of wind power in India and Tamil Nadu.

the land and the weaker north-east winter monsoon, which starts in October, when dry air moves towards the ocean. During the period March to August, the wind is uniformly strong over the whole Indian peninsula, except the eastern peninsular coast. The speed of the wind during the period November to March is relatively weak, though higher winds are available during a part of the period on the Tamil Nadu coastline.

Wind power has been concentrated in a few regions, especially the southern state of Tamil Nadu, which maintains its position as the state with the largest wind power installation, with 7154 MW installed until February 2013, representing 39% of India′s total installed capacity. Tamil Nadu being the first state to introduce wind farms in the country has achieved tremendous success in harnessing renewable energy for generation of grid quality power. The state is endowed with three prominent passes having high wind potential namely, Aralvaimozhy pass in Kanyakumari District, Shengottah pass in Tirunelveli District and Palghat pass in Coimbatore District. The average annual wind velocity for the above locations is assessed as 19–25 km/h, 18 22 km/h and 18–22 km/h respectively. Recent study has identified some wind potential sites in coastal area near Chennai, Rameswaram, Palani and Theni.

The development of wind power in the whole of India and only Tamil Nadu during the last six years is illustrated in Fig. 1. The World Institute of Sustainable Energy predicts an annual market of 5000 MW of wind power by the year 2015. Emerging technologies like repowering, offshore wind, etc., are also being explored.

3. Theory of wind turbine generators

The principal components of a modern horizontal axis wind turbine generator (WTG) are the tower, the rotor, nacelle assembly and controller. The nacelle accommodates the gear transmission mechanisms, braking systems, generator and the yaw system for steering in response to changes in wind direction. Switching and protection systems, transmission lines, transformers will also form the part of a wind farm [7].

3.1. System description

Certain investigations are done in a 10.02 MW wind farm at Aralvaimozhy pass Muppandal area in Tamil Nadu, India, having various models and capacities of WTG. The performance of a specific group of 250 kW, Danish machines in the wind farm is found to be low when compared to the neighboring different make machines of same capacity.

3.2. Design configuration

The wind turbine rotor in the said group of WTG consists of a hub, rotor blades and blade extenders to increase the rotor diameter to 25 m and hence the swept area. The hub is made from cast steel and mounted directly on the rotor shaft. The three rotor blades are made up of glass reinforced plastic molded on a steel shaft with turnable blade tip air brakes. The major criteria for this material selection are fatigue strength, specific weight, admissible stress, modulus of elasticity and breaking strength. The configuration and the major components of the WTG are depicted in Fig. 2.

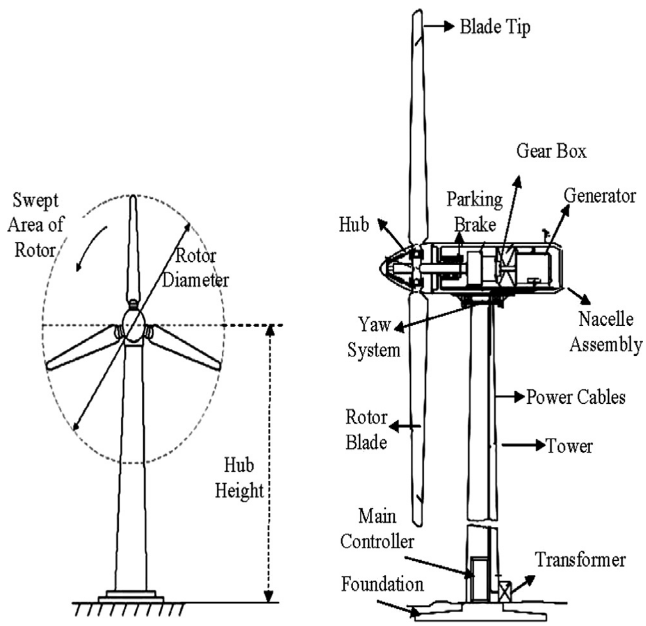

Fig. 2. Configuration and major components of a WTG.

The mechanical energy from the wind turbine rotor is stepped up by suitable gear transmission, which couples the rotor and the generator. The very high efficiency of the transmission is reflected by the extreme low levels of noise emission, vibration and temperature rise during operation. The integrated gearbox is designed to transmit all static and dynamic forces directly into the tower construction. It has 3 stages with 4 parallel shafts. The low speed shaft is hollow and manufactured in one piece with a flange for direct mounting of the rotor. Gears increase the rotational speeds from about 30 to 40 rpm to about 900 to 1000 rpm, the rotational speed required by most generators to produce electricity. This mechanical energy is converted into electrical energy using an induction generator and the power thus generated may be supplied to the grid. This power is transferred through the copper cables connecting the controller located at the base of the tower. The power flows through heavy aluminium cables from the controller to the power transformer located outside which steps up the voltage to the transmission voltage level.

The brake system is of negative fail-safe type and consists of three independent aerodynamic brakes and a parking brake with primary and secondary functions controlled by a hydraulic pump unit. An active hydraulic pressure keeps the blade tips in operation, but as soon as a stop command is encountered or at any loss of electrical power from the grid, the oil pressure drops which instantly releases the airbrakes. The parking brake is a fail-safe unit with a built in spring activated braking force. The brake disc is mounted on the high speed shaft. An active hydraulic pressure keeps the brake caliber in the open position. Instantly the airbrakes will decrease the rotor speed. At 40% of the nominal rotor speed, the parking brake will be activated and the rotor is brought to a complete stop. A fiberglass cover protects the components inside the nacelle. Some nacelles are large enough to accommodate few technicians while working. Fig. 3 illustrates the sketches of gear box and yaw system.

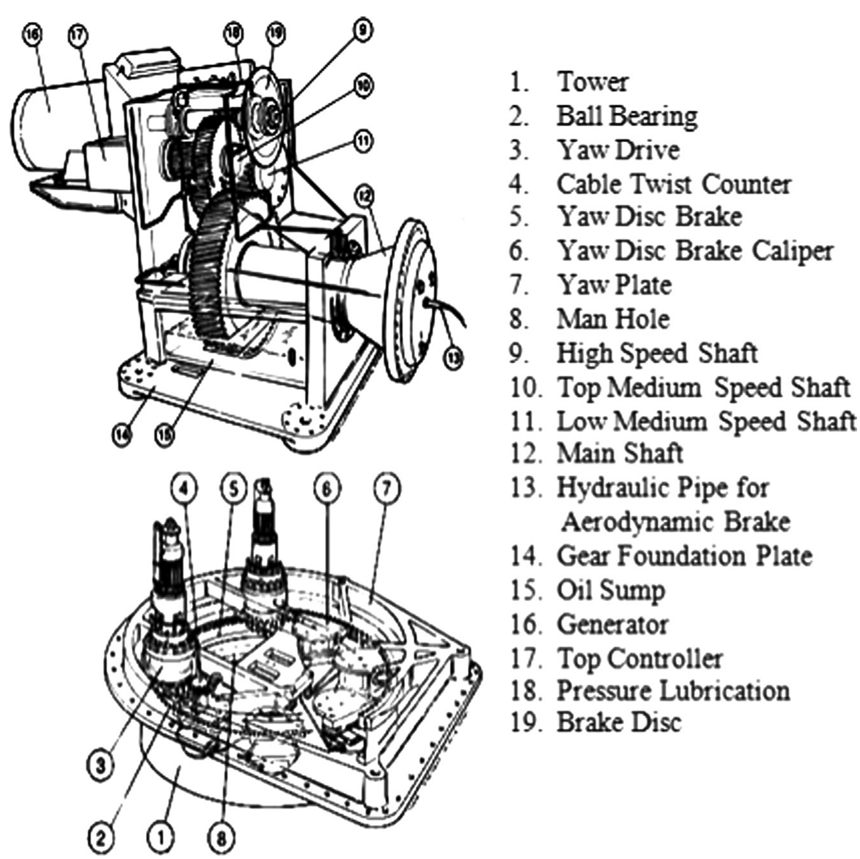

Fig. 3. Illustration of gear box and yaw system.

The tower is used to support the entire nacelle assembly along with the rotor above the ground level. Towers are made from tubular steel or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity. In addition, it is used to absorb and securely discharge static and dynamic stress exerted on the rotor and the nacelle assembly into the ground. The tower is made up of steel. The rotor radius determines the minimum tower height.

The nacelle assembly along with the rotor is placed over the tower through a yaw system. Anemometer on the nacelle top is used to measure the wind speed and transmits wind speed data to the controller. The wind vane, which is also located on the top of the nacelle, senses the maximum wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind. Yaw motor powers the yaw drive. The control signal from the controller releases the yaw brakes and the entire nacelle assembly is oriented towards the maximum wind direction. The yaw drive system consists of a yaw mounting plate of cast steel, a ball bearing slew ring with inside cogging, one or two electrical yaw gear units and a friction system to dampen the yaw movements. The complete system is mounted on the top of the tower flange.

The heart of the WTG is the microprocessor based controller that controls the entire operation located at the base of the tower. It carries out the basic monitoring, control and safety operations such as monitoring of brake system yaw control, cut-in and cut-out of the generator to the grid and monitoring of user defined or fixed limits for operation. For later analysis and fault diagnosis, various statistical data regarding the performance of the turbine and record of accomplishment of faults are collected and recorded. The controller starts up the machine at wind speeds of about 3.5 m/s and shuts off the machine at about 25 m/s. Turbines cannot operate at wind speeds above 25 m/s because the tower will not withstand dynamic loads beyond this value. In addition, the generators could overheat. The controller cabinet has separate housings for soft switching equipment, contactors for generators and motors, overload relays, circuit breakers, and capacitor banks.

4. Investigations related to yaw system in performance enhancement

4.1. Yaw error problems

These WTG are equipped with hydraulic yawing unit with negative fail-safe braking system. The yaw mechanism that is used to turn the rotor and nacelle against the wind is operated electrically

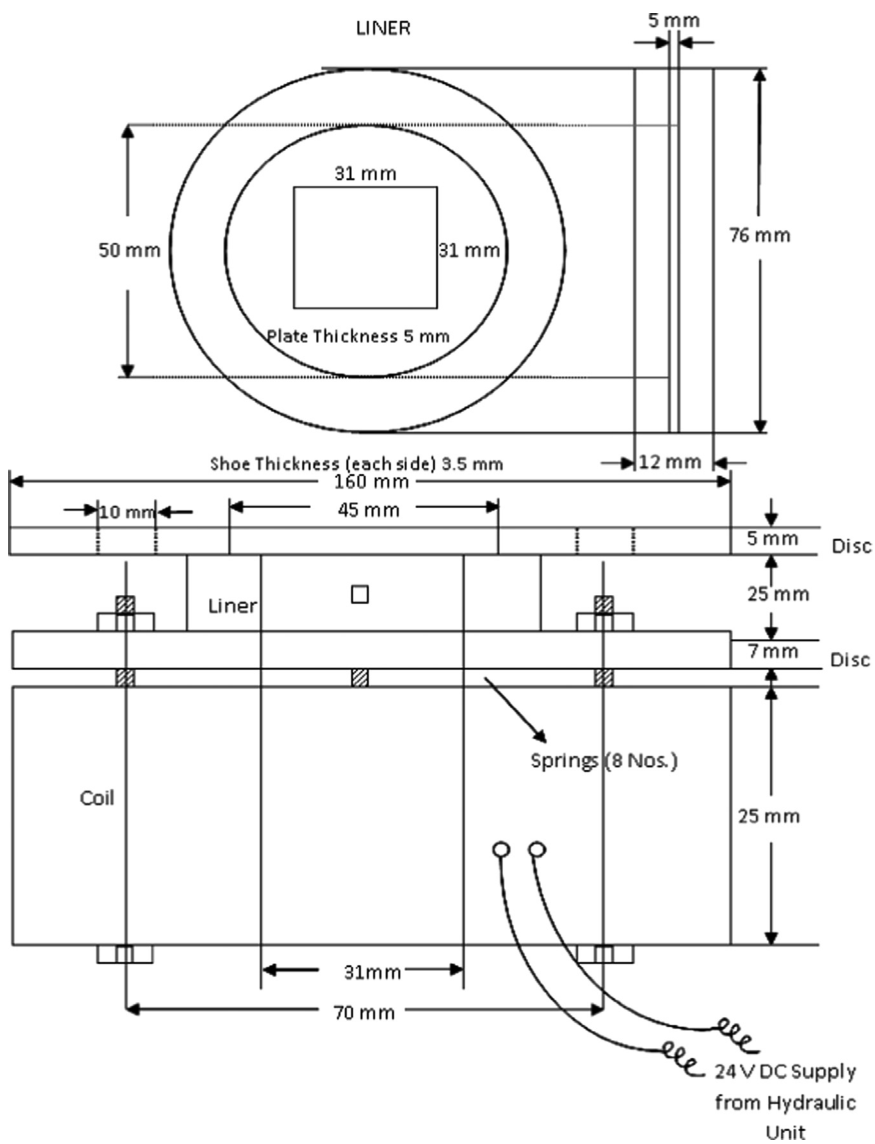

Fig. 4. Design of new electromagnetic yaw braking system.

and controlled by the controller based on the information from wind vane. It consists of a yaw mounting plate of cast steel, a ball bearing slew ring with inside cogging, a two stage electrical yaw gear unit with gear ratio of 1:1218.875 and equipped with three phase induction motor of 0.37 kW rating and a friction to dampen yaw movements. The yaw movement is dampened by five yaw brakes out of which, three are hydraulically activated and two mechanically operated. In this regime, the yaw motor will normally run frequently due to turbulence in wind stream for about 50 times a day.

If the rotor is not perpendicular to the wind direction, yaw error occurs. It implies that the wind energy harnessed by the rotor area is lesser. Hence appropriate yaw control is required to control the power input to the wind turbine rotor. The part of the rotor, which is closest to the wind direction, will be subjected to a larger force than the rest of the rotor. Hence, the rotor will have a tendency to yaw against the wind automatically. As the wind gusts are severe in this regime, the yaw brakes allow some restricted yaw movements to avoid peak loads in the yaw drive system. Thus, the yaw gear unit failure is more frequent and yaw hydraulic brakes are not sufficient to control the orientation of nacelle assembly towards predominant wind direction. Hence, the power capturing capacity is reduced.

4.2. Remedial measures

To overcome this problem, an electromagnetic brake replacing yaw hydraulic brake is suggested. The main requirements to be considered are high reliability, low maintenance and a low braking torque tolerance. In the existing system, the hydraulic yaw brake and the mechanical brake are provided on the high speed shaft of the yaw system located on the slew ring.

By detailed investigations, it is proposed to have an additional electromagnetic braking on the high speed shaft and the hydraulic yaw brake is operated as mechanical yaw brakes on the low speed shaft. The hydraulic unit has three controls for parking brake, aerodynamic brake and yaw brake respectively. The solenoid coil corresponding to the existing yaw brake is used for electromagnetic braking. In addition, the cooling fan of the yaw motor is removed and the electromagnetic brake is mounted on the shaft with some mechanical arrangements. As the yawing is not so frequent in a day, the motor is not under operation continuously. Hence, the cooling fan is not required in this application. In addition, as the nacelle is highly ventilated and the yaw system is located about 30 m from the ground level, natural cooling of yaw motor is sufficient.

4.3. Design of electromagnetic yaw braking system

The electromagnetic yaw brake consists of field, armature and hub. The magnetic field is bolted to the yaw motor shaft. When the armature is attracted to the field, the stopping torque is transferred into the field system and hence into the yaw shaft decelerating the load. Similarly when the supply to the coil is cut-off, the magnetic flux falls rapidly and the armature gets separated. Eight springs hold the armature away from the disc surface at a predetermined air gap.

The new braking system will keep the nacelle to face the predominant wind direction. In the event of a fault, the brakes will act as a friction clutch to enable the nacelle to move with the wind. The design details of proposed electromagnetic yaw braking arrangement are shown in Fig. 4. The entire system is designed based on the available measurements in the yaw component. As the cooling fan is removed, the space is adequate to fix the discs on the yaw gear shaft. The control of electromagnetic braking system is done with the existing microcomputer based controller. The execution code is changed to send control signal to the braking system depending upon the maximum wind direction.

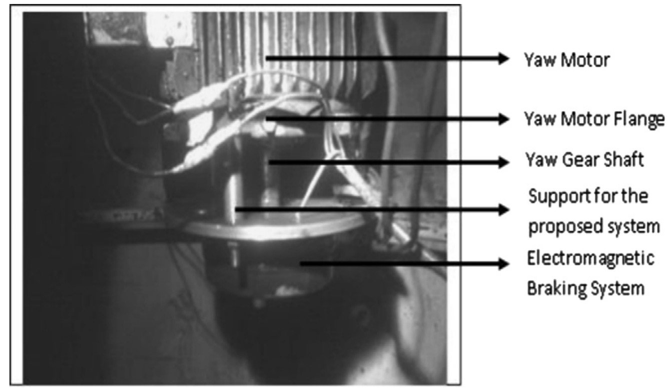

Fig. 5. Snap shot of new electromagnetic yaw braking system.

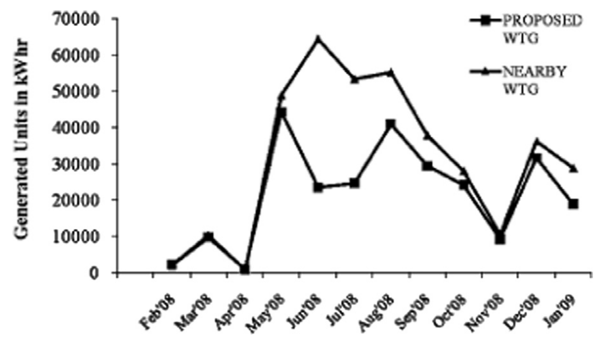

Fig. 6. Performance characteristics before installing new electromagnetic yaw braking system.

Fig. 5 illustrates the snap shot of the proposed system incorporated in the existing WTG which is under satisfied operation for the last two years.

4.4. Performance analysis

On implementation in a WTG, the performance analysis is made for two years duration before and after installation. The performance measures considered for the study are generated units in kW h, capacity factor and generated units per running hour for the years from 2008. The capacity factor is defined as the ratio of the electrical energy produced by a WTG for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period. The running hour of WTG is the actual operating hour that excludes the machine stoppages due to grid failure, machine failure etc. The yaw brake was installed during the end of January 2009 and hence the monthly data are collected and recorded for the duration from February 2008 to January 2010. An interesting fact that was observed from the collected data is the running hours and the generated units for the similar months in the two consecutive years are not comparable. For instance, the running hours during February 2008 was 109 h and during February 2009 was 510 h. As the grid availability was not proper during 2008, there was a decrease in running hours. Hence the performance details of another Danish model of neighboring machine of same 250 kW rating are also taken for analysis. The rotor diameter of the nearby WTG is 29 m while the rotor diameter of the proposed WTG is 25 m. Hence the performance of the nearby WTG is slightly higher than the proposed WTG.

Figs. 6 and 7 show the performance characteristics of the proposed WTG and the nearby WTG of different make and same

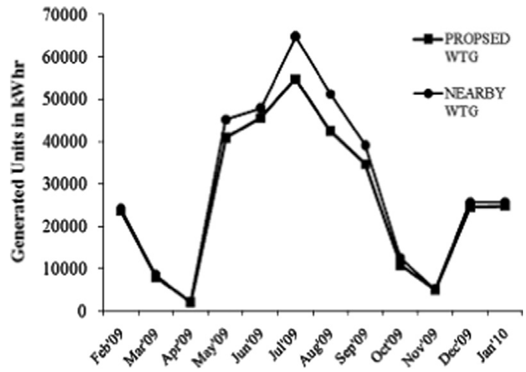

Fig. 7. Performance characteristics after installing new electromagnetic yaw braking system.

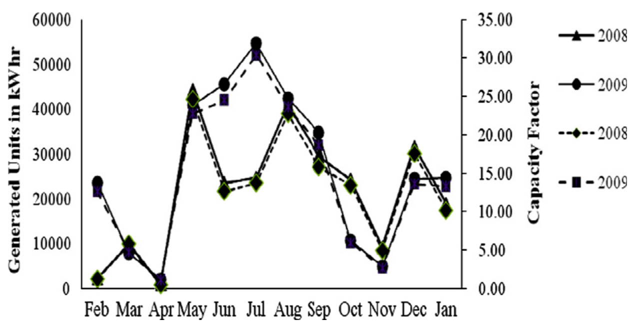

Fig. 8. Performance characteristics before and after installation.

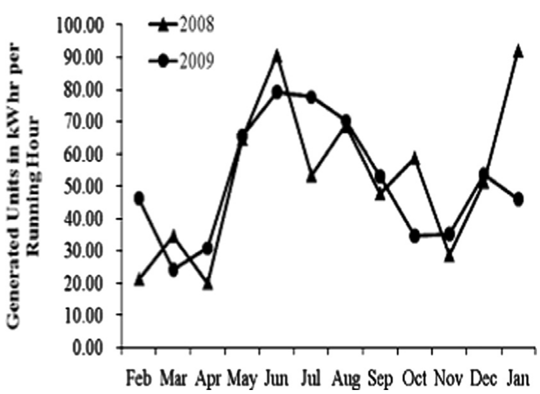

Fig. 9. Generated units in kW h per running hour before and after installation.

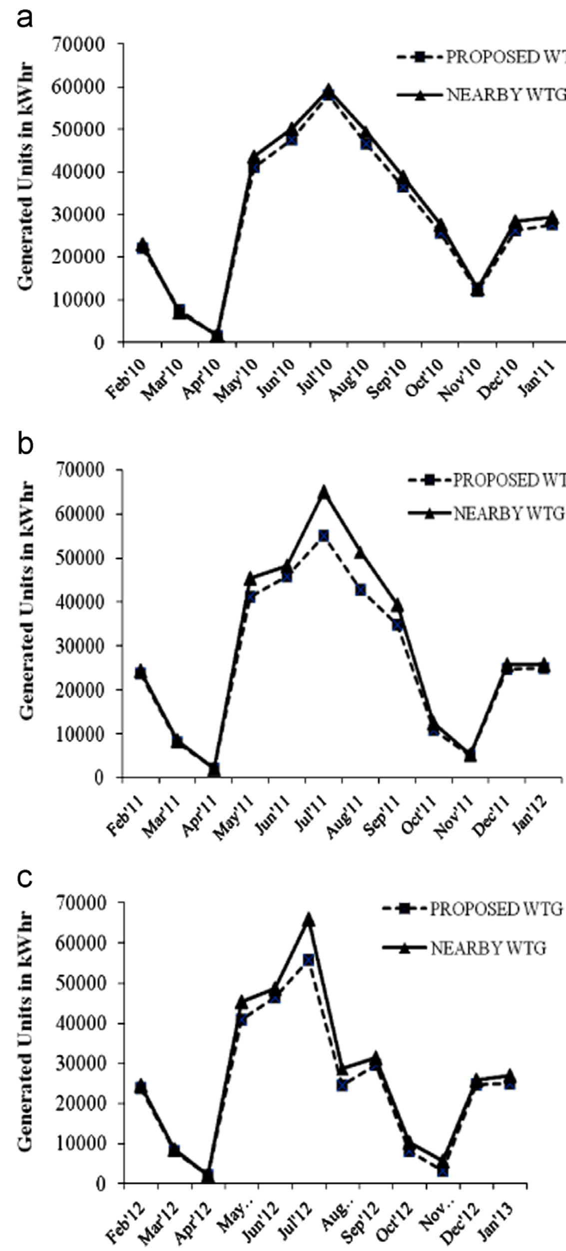

Fig. 10. Performance characterisitcs of the propsoed WTG and nearby WTG.

capacity for duration of two years. It is observed from Fig. 6, that the generation is affected during peak wind periods i.e. from June to October and hence the generated units from the proposed WTG are 35% lesser when compared to the nearby WTG. Whereas the generation during low and medium wind periods is also lower about 10%. After installing the electromagnetic yaw braking system, the performance characteristics in Fig. 7 illustrates a significant improvement in the generation of the proposed WTG. During the same peak wind period, the difference in the generation between the proposed WTG and nearby WTG is only 12%.

The performance analysis based on the generated units and capacity factor before and after installing the new electromagnetic yaw braking system are depicted in Fig. 8 The generated units in kW h show a significant improvement as depicted in Fig. 8, in the year 2009 compared to the previous year i.e. before installing the porposed braking system. It is clear that during peak wind period, the generation is more than the medium wind period. From the characteristics shown in Fig. 8, it is obvious that during 2009, there is an average increase of about 15% in capacity factor. As the running hours of similar months in the two consecutive years are not comparable, the generated units in kW h per running hour is computed for the said period and comparison characteristics are drawn as shown in Fig. 9. On an average, a 10% increase is observed from the performance particulars.

It is observed that the effectiveness of the yaw system is enhanced. This improves the life of yaw gear unit and avoids oil spills in the yaw brakes, thus increasing the power generation capacity. The failure of yaw gear unit has been drastically reduced after installing the electromagnetic braking system by an average of 2 times a year when compared to 6 times a year before installation. As the nacelle assembly is facing the predominant wind direction almost all the time, the pressure on the yaw gear to overcome the wind gusts is reduced. The management of the wind farm owns an industry in south Tamil Nadu. The power produced from the WTG is adjusted with the power consumed from TNEB in their industry. The present tariff of power consumed @ Indian Rupees. 4.00 per kW h yielded an increase of Indian Rupees 2.27 Lacks during the year 2009. Thus, the minimal modifications in the existing system with optimum design of electromagnetic braking have increased the efficiency of the WTG and also the revenue for the wind farm owner is consistently improved. As the results are encouraging, the entire similar model WTG in the wind farm are presently equipped with new electromagnetic yaw braking system.

To study the effectiveness of the proposed design, the generation particulars for the consecutive three years have been collected and analysed. The performance of the proposed WTG compared to the nearby WTG for the years 2010, 20111, 2012 are depicted in Fig. 10.

The improvement in power production is calcluated for all the years from 2008 to 2012 and the percentage improvement in units generated from the propsoed WTG and the nearby WTG are illustarted using the bar chart shown in Fig. 11. This shows a very interesting fact that the efficeincy of the WTG is consistently improved due to the inclusion of the proposed electromagnetic yaw braking system from the year 2009 as the running time of the WTG is increased even due to medium wind speed. As the running time differs for each year due to field problems such as grid unavailability, climatic conditions etc., the performance of the nearby WTG is considered for comparison purpose.

Further analysis is made based on the generated units per running hour and capacity factor of the WTG, to compute the percentage improvement in power production from the year 2008 to 2012. The percentage improvement in power production are represented with the aid of pie-chart in Fig. 12. It is observed that an average increase of 22.90% is achieved after the installation of proposed electromagnetic yaw braking system. As the power produced from the WTG is adjusted with the power consumed from TNEB in their industry, based on the tariff of power consumed @ Indian Rupees. 5.00 per kW h yielded an increase of Indian Rupees 11.94 Lacks from the year 2009 to 2012.

Now the proposed design is installed in all the WTGs of same type in Muppandal area and in Kethanoor area. As there are around 5000 WTGs of similar type located in this turbulent wind regime, the new braking system is being installed in almost all the WTGs of similar type.

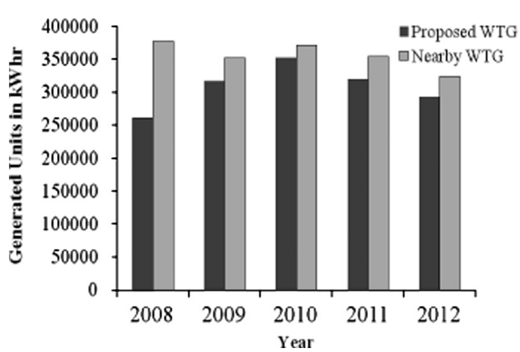

Fig. 11. Comparison chart of generated units before and after installation.

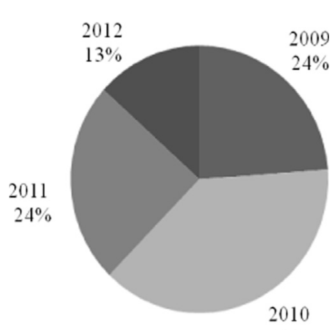

Fig. 12. Percentage improvement in production.

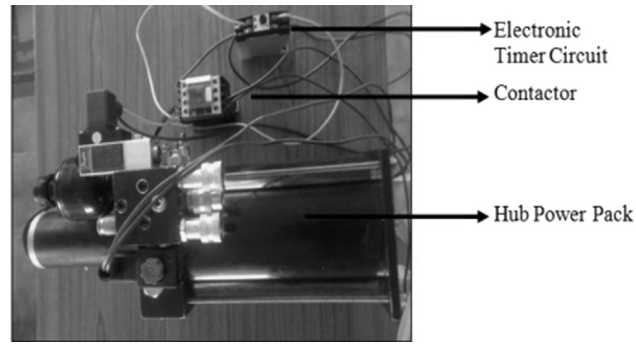

Fig. 13. Snap shot of hydraulic power pack with proposed design.

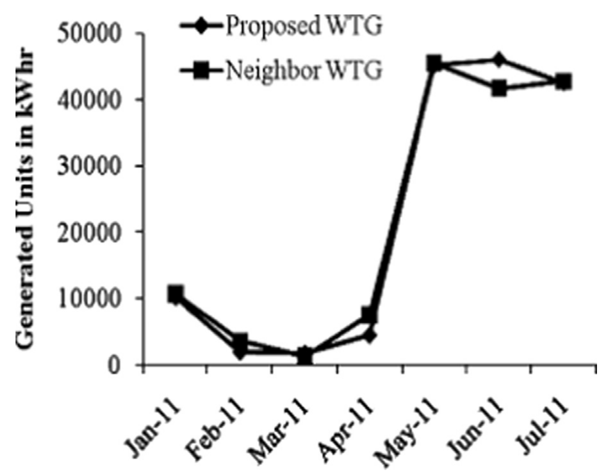

Fig. 14. Generated units in kW h before and after installing proposed circuit.

5. Investigations related to hub hydraulics in performance enhancement

In another Indian model of 250 kW WTG, frequent failures of hub power pack and rotor hydraulic brake systems constantly occurred. This particular model uses two hydraulic systems for aerodynamic brakes and parking brakes respectively. In the hub power pack, the hydraulic motor frequently failed to operate. The failure rate was more and hence the machine down time rapidly increased. This decreased the capacity factor of the WTG.

5.1. Suggested solution

An in depth analysis has been made and the major reason for down time is found to be the overheating of hydraulic motor due to its continuous operation as the pressure to be build up in the accumulator is inadequate. The pre-charging of N_2 gas pressure in the accumulator was found to be insufficient. For satisfied operation, a hydraulic pressure between 80 and 90 bar is required keep the rotor blade tips in alignment with the blade. The existing hydraulic power pack was modified such that the motor is made to run with the aid of an extra 555 timer circuit and a 9 A contactor. The average time for building up the required hydraulic pressure was studied and found to be less than one minute. Hence a 555 timer is connected to operate the motor for about one minute so that the motor will stop after this time irrespective of the pressure developed. This has been installed in a WTG during May 2011 and

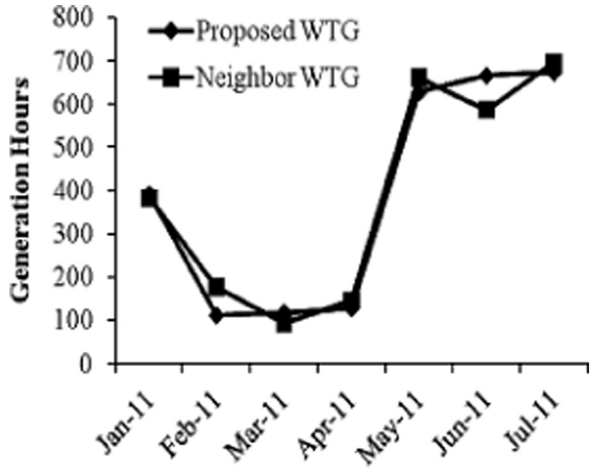

Fig. 15. Generation hours before and after installation.

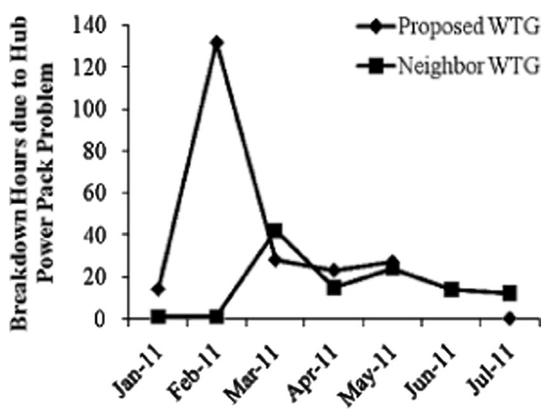

Fig. 16. Breakdown hours due to hub power pack before and after installation.

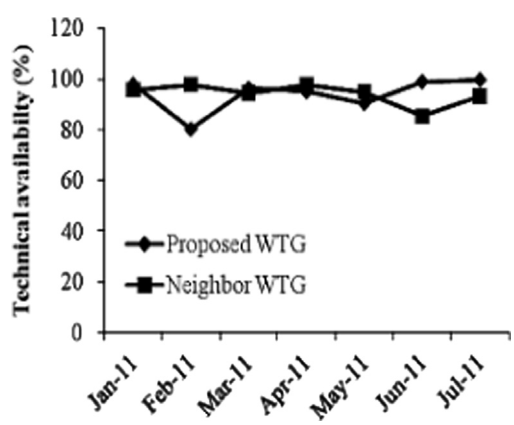

Fig. 17. Technical availability before and after installation.

tested. The snap shot of the electronic circuitry installed in a hub power pack is shown in Fig. 13.

5.2. Performance analysis

The performance analysis of the proposed design is made and the comparison characteristics are drawn. The generated units in kW h is compared with the nearby WTG of same model and as illustrated in Fig. 14, a 2% increase in generation for the period after installing the timer circuit is produced.

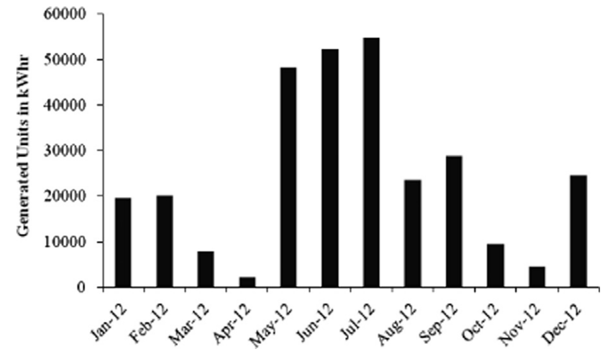

Fig. 18. Performance of proposed WTG for the year 2012.

The total generation period for the proposed WTG is 1969 h for a period from May 2011 to July 2011 while for the nearby WTG is only 1945 h. After installing new control circuit in hub power pack, the generation period is increased by 239 h that results in significant increase in power production, as it was peak wind season. It is also observed that the machine break down hours due to failure in hub power pack in the proposed WTG is nil while that for the nearby machine is 142 h. Hence, the technical availability of the WTG after modification is 96.28% when compared to 92.28% before installing the timer circuit. These are illustrated in Figs. 15–17.

The major break down in the WTG is due to the failure of the hub power pack and this drastically reduces the running hours of the WTG. In addition, the technical availability in the nearby WTG without any modification in the hub power pack for the entire wind season is only 91.12% while for the WTG with modification 95.03%. Thus the failure rate of hydraulic hub power pack is drastically reduced, so that the operation and maintenance cost is minimized.

The performance of the proposed WTG is also analysed for the year 2012. The generated units in kW h for the entire year 2012 is shown in Fig. 18. The machine break down of the proposed WTG is only 47 h while compared to the previous year's value of 320 h. The technical availability for the year 2012 is 97.58% which has a significant increase of around 6% when compared to the previous year i.e. before installing the timer circuit. This encouraging performance made the wind farm owners of that area to install the proposed control circuit in all the WTGs of similar type.

6. Conclusion

The practical aspects of the commercial wind farms related to significant operation of yaw system and hub hydraulics are discussed. In addition, manufacturing design modifications to suite Indian atmospheric and grid conditions to enhance the power production are presented in detail with the aid of case studies.

The remedial measures to reduce the down time of the WTG due to few critical issues such as yaw errors and failure of hub power packs are proposed and implemented in the existing systems. The results are encouraging in terms of power production, machine stoppage and reduced operation and maintenance costs as certified by the wind farm owners and the same are being implemented in other plenty number of WTGs of similar models located in southern Tamil Nadu.

Appendix

Type	Horizontal axis, up-wind oriented
Capacity	250 kW
Rotor speed	40 rpm

Rotor diameter	29.8 m
Air density	1.2 kg/m^3
Regulation	Stall
Blade pitch angle	-1.1°
Gear box ratio	1:24.52
Cut-in wind speed	3.5 m/s
Cut-out wind speed	25 m/s
Rated wind speed	15 m/s
Equivalent inertia	1542 kg m^2

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