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MULTI-CRITERIA DESIGN OPTIMIZATION OF PITCH BEARING FOR WIND POWER GENERATION SYSTEM APPLYING ARTIFICIAL INTELLIGENCE TECHNIQUES FOR ENHANCED RELIABILITY

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Abstract

Profligate industrial development and incompetent handling of hydro-carbon-based fuels have led to global warming. The unusual heating of the surface air has consistently deteriorated the ecosystem comprehensively through erratic weather patterns and consequential upsurge of sea water level. The worsening conditions of the environment have triggered socio-economic disasters and compelled the international community to enforce the Paris Agreement of 2015 to constrain the emission of greenhouse gases. The power generation sector is one of the leading contributors to worldwide greenhouse gas emanation. Pertinent growth of renewable energy techniques such as wind power can help power generation businesses to lessen greenhouse production substantially. Globally, a considerable portion of the operating time of wind power generation systems is wasted every year owing to mechanical malfunctions of its several parts. Pitch bearing is an imperative component of the wind power generating unit which facilitates the wind turbine blades to maintain the appropriate alignment required for achieving the maximum power generation capability. In this paper, the design of the pitch bearing has been optimized using artificial intelligence methodologies like Genetic Algorithm and JAYA Algorithm. Objectives like L10 life and static load factor have been deemed for maximization whereas the bearing frictional torque has been considered for minimization. The optimal designs achieved using the aforementioned artificial intelligence techniques have been contrasted. The JAYA Algorithm is more beneficial than the Genetic Algorithm for enriching the reliability of operation for the wind turbine pitch bearing.

Keywords: Bearing Life, Design Optimization, Frictional Torque, Genetic Algorithm, Jaya Algorithm, Static Load Factor, Wind Turbine

JEL Classification: -

1. Introduction

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The unremitting expulsion of greenhouse gases to the ecosystem attributable to an assortment of societal commotions is accelerating global warming and aberrant meteorological conditions. Unsustainable usage of hydrocarbon-based non-renewable fuels is furthering the greenhouse impact and is momentously accountable for the atypical upsurge of global warming.

To inhibit the catastrophic outcome of climate change, a record number of associates of the United Nations have approved to authorise an intercontinental accord in Paris in 2015. This pact directs the competent handling of renewable supplies of electricity like wind power to impede the emanation of greenhouse gases all through the Planet.

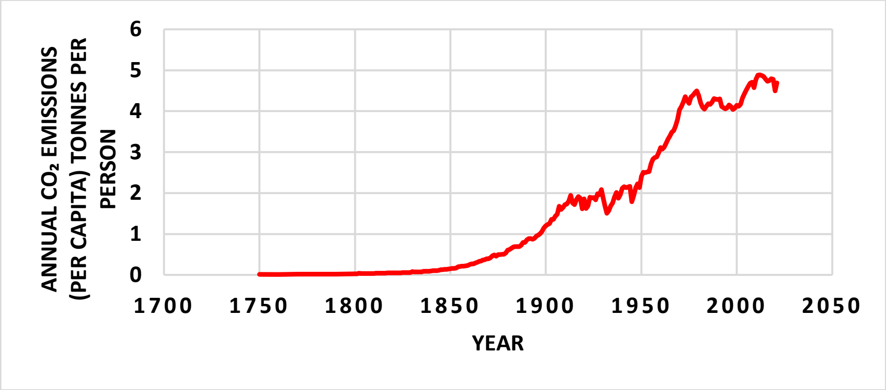

Figure 1: Global Yearly CO_2 Emissions (Per Capita) Tonnes Per Person

Because of the wide-reaching trepidation for the impeded supply of non-renewable fuels, renewable power generation technologies impart abounding replacements. The percentage of renewable power in general power generation has broadened in the past three decades progressively which is a realistic sign of worldwide leaning in the direction of low-carbon substitutes of energy means.

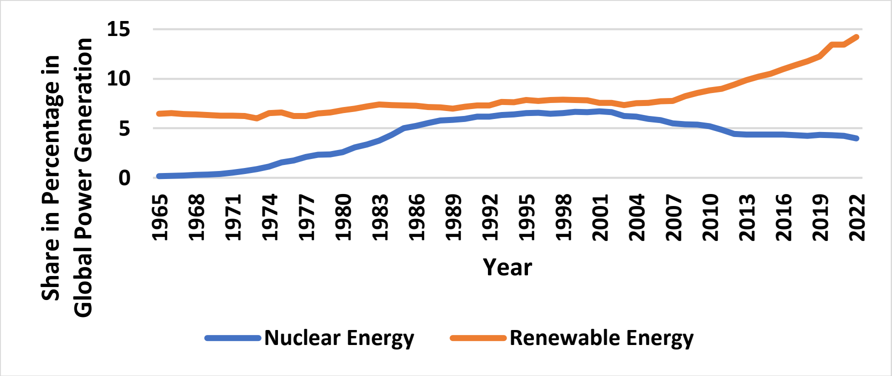

Figure 2: Share of Primary Energy of Renewable and Nuclear Sources

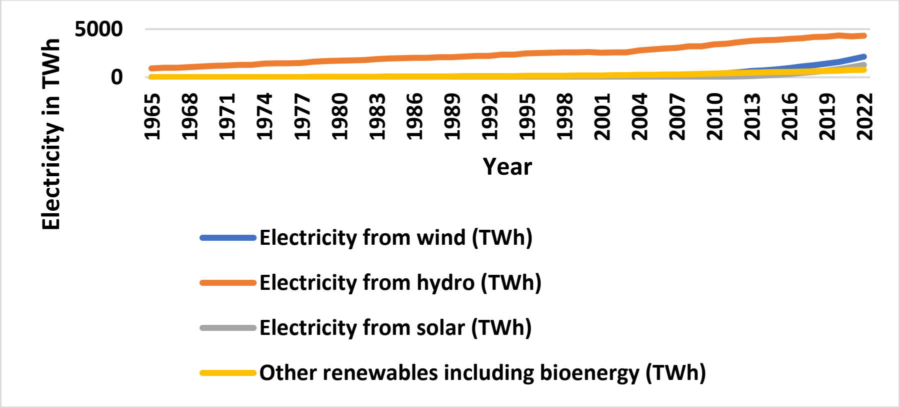

Figure 3: Growth of Renewable Energy Generation from Different Sources

In consort with the minimal emanation lead, renewable power techniques such as wind power are entailed to remain sustainable with insinuating cost-effective generation charge as a result of exceptional reliability and nominal charge. Consequently, apposite emphasis is required to be upheld throughout the wind turbine design stage to minimize the possibility of interruption through the operative cycle.

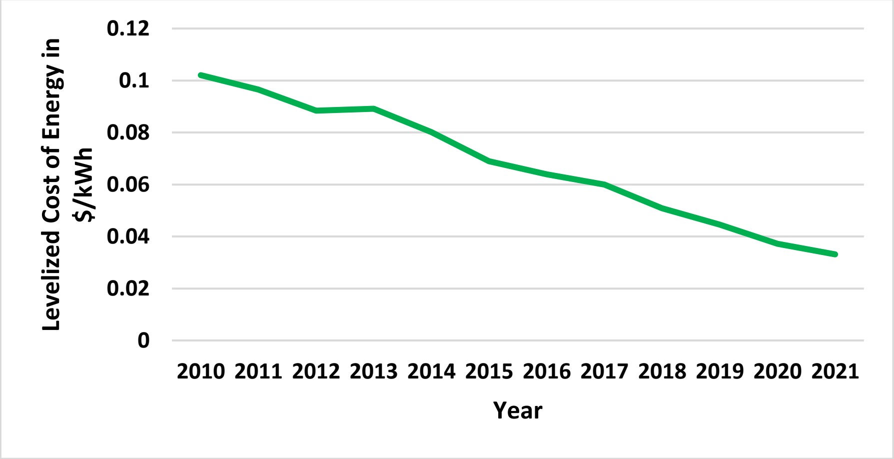

Figure 4: Decline of Levelized Cost of Energy for Onshore Wind Power (2010-2021)

Market studies testify that mechanical malfunctions of wind turbines are responsible for nearly 56% of the entire charge of insurance petitions and 33% of the overall number of demands listed for wind turbines. The income deficits borne by wind power businesses because of turbine breakdown can fluctuate from 200 M€ in Spain or 700 M€ in the whole area of Europe to 2200 M€ in other parts of the Globe. These forfeitures can soar to three times if the operative overheads are considered.

Van Bussel and Zaaijer (2001) studied numerous facets of the operation and upkeep of wind turbines. They estimate 2.20 breakdowns per year for a wind turbine. They observed that the pitch system has a higher vulnerability for failure. The pitching mechanism was accountable for 0.28 malfunctions per year. Tavner et al. (2005) evaluated the malfunction frequencies of German and Danish turbines applying the reliability data and power law technique. They detected that Germany-manufactured turbines had to some extent higher chance for failure and were expected to have similar breakdown rates of Denmark-made turbines after 7 years. Shokrieh and Rafiee (2006) offered a three-dimensional finite element prototype for the fatigue breakdown of composite wind turbine rotor blades. Because of the unpredictability of the airflow configuration, a stochastic procedure was involved in planning the software scheme. Echavarria et al. (2008) analysed the failure of a 250 MW wind turbine using a test database. They perceived that the failure rates were lessening with time. Chen and Kam (2011) reported a malfunction assessment of composite wind turbine blades utilizing ANSYS. They utilized the finite element analysis to observe the stress dispersal and whiffle-tree technique for modelling the wind loads. Afterwards, the computed extreme load was confirmed for breakdown scrutiny. Gallego-Calderon et al. (2015) considered the impact on reliability for both cylindrical and tapered roller-type planetary bearings of wind turbine gearboxes. They utilized MATLAB codes and normal design load cases for computing the reactions at numerous speeds. The tapered roller-type arrangement confirmed superior reliability and dynamic load rating. Stammler et al. (2018) studied the effect of oscillation on the damage lifetime of pitch rolling bearing of wind turbines. They utilized time series data and stochastic airflow form. It was resolved that cycle counting is more competent than the rain flow counting technique. Schwack et al. (2020) examined the consequence of grease lubricants on the abrasion of the wind turbine pitch bearing. The grease lubricants with nominal base oil viscosities and elevated bleeding rates were recommended for better performance.

In the present paper, the multi-criteria design optimization of the pitch bearing of the wind turbine has been performed. Maximization of L_{10} life, minimization of the bearing frictional torque and maximization of static load factor have been considered as the objectives. Due to the complexity of the deemed problem, artificial intelligence techniques have been utilized. Meta-heuristic methodologies such as the Genetic Algorithm and JAYA algorithm have been employed to optimize the deemed objectives. The solutions attained through both artificial intelligence methods have been compared to find out the better technique for optimizing the design of the wind turbine pitch bearing.

2. Objective Construction

Pitch bearing, which is on the other hand recognized as blade bearing, is that element of the wind turbine which ties the hub and blade of the rotor. It enables to handle the loads and power of the turbine by allowing the essential oscillation. The pitching procedure is applied to uphold the WT rotor blade to the necessitated setting by regulating the aerodynamic angle of attack.

Rolling element bearings utilized in the pitching system are impacted by radial and axial forces and turning moments concomitantly. The bearings are manufactured utilizing two ring-rolled forged components forming the exterior and interior conduits.

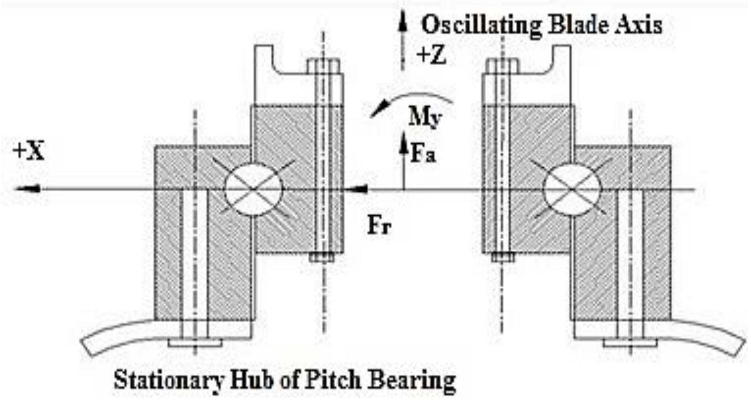

Figure 5: Pitch Bearing of Wind Turbine

Rolling element bearings are of uncomplicated exterior geometry but their internal geometry can have enormous significance on numerous factors like permitted stress and load dispersal.

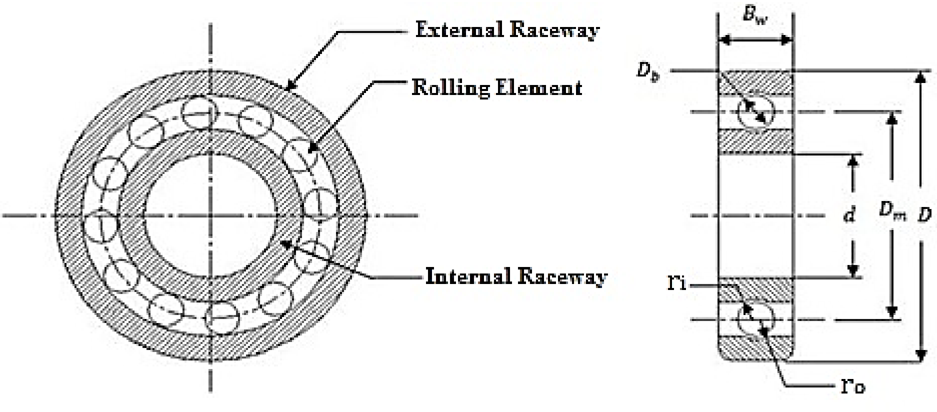

Figure 6: Rolling Bearing Design

The terminology of variables employed in the current research work with their explanation has been shown in Table 1.

Variable Symbol	Description
B_w	Bearing Width, mm
c_1, c_2	Parameters to Calculate Contamination Factor, dimensionless
d	Bore Diameter, mm
D	Outer Diameter, mm
D_b	Rolling Element Diameter, mm
D_m	Pitch Diameter, mm
e	Parameter for Rolling Element Mobility Consideration, dimensionless
$f_i\,(=\dfrac{r_i}{D_b})$	Curvature Co-efficient of Inner Raceway, dimensionless
$f_o(=\dfrac{r_o}{D_b})$	Curvature Co-efficient of Outer Raceway, dimensionless
i	Number of Rows of Rolling Elements
$K_{D_{max}}$	Maximum Ball Diameter Limiter, dimensionless
$K_{D_{min}}$	Minimum Ball Diameter Limiter, dimensionless
l_e	Roller Effective Length, mm
r_i	Inner Raceway Curvature, mm
r_o	Outer Raceway Curvature, mm
z	Number of Rolling Element per Row
α	Contact Angle, degree
ɧ	Raceway Hardness, HRC (Rockwell C Scale Hardness)
ε	Parameter for Outer Raceway Strength Concern, dimensionless
ζ	Parameter for Rolling Element Diameter Calculation considering Bearing Width, dimensionless
κ	The measure of Sufficiency of Lubrication, dimensionless

μ	Co-efficient of Friction, dimensionless

Table 1 Terminology of Variables

2.1 Modified L_{10} Life According to ISO Standard 281 (L_{ISOm})

The lifespan of a bearing is considered as the number of revolutions one of the bearing conduits finishes for the other race before the preliminary symptom of fatigue being imperilled in the material of one of the conduits or spinning components. L_{10} lifespan can be computed in hours of working as per Eq. 1.

$$L_{10}\,(in\,hr) = \frac{L_{10}.10^6}{N.60} \tag{1}$$

Following the ISO standard 281, bearing fatigue lifespan with the ball in millions of revolutions has been stated in Eq. 2.

$$L_{ISOm} = a_1 a_{ISO} \left(\frac{C_a}{P_{ea}}\right)^3 \tag{2}$$

a_1 and a_{ISO} are geometry-dependent parameters.

2.2 Bearing Friction Torque (*T*)

The frictional torque of the bearing is a crucial design factor for assessing the shortfall of the transferred power besides for the management of the revolving system. Frictional torque is caused because of friction between two surfaces in connection and its appropriate computation for the pitch system is crucial for fabricating the drive and actuator mechanism. Bearing friction torque for the pitch system can be calculated as per Eq. 3.

$$T = \mu \frac{D_m}{2} \left(\frac{4.4M}{D_m} + 2.2F_r + F_a\right) \tag{3}$$

2.3 Static Load Factor (SF)

The static load factor has been defined as the ratio of the permissible load to the existent load. It must be greater than 1 to guarantee some allowance of safety concerning the static capacity. The static load factor for ball bearing is computed as per Eq. 4-6.

$$SF = \left(\frac{4000}{S_{max}}\right)^3 \tag{4}$$

$$S_{max} = \frac{1.5Q_{max}}{\pi ab} \tag{5}$$

$$Q_{max} = \left(\frac{2F_r}{z\cos\alpha} + \frac{F_a}{z\sin\alpha} + \frac{4M}{D_m z\sin\alpha}\right) \tag{6}$$

Where, F_r, F_a and M are transferred radial load, thrust load and moment respectively.

3. Constraints

The constraints of an optimization conundrum split the viable parameter area, where every constriction is satisfied, from the unfeasible space where nonetheless one of the restraints is confronted. This research paper implemented the restraints demarcated by Duggirala et al. (2018) and they have been defined as per Eq. 7 - 17.

$$\phi_0 = 2\pi - 2\cos^{-1}\frac{\left[\left\{\frac{(D-d)}{2}-3\left(\frac{T}{4}\right)\right\}^2+\left\{\frac{D}{2}-\left(\frac{T}{4}\right)-D_b\right\}^2-\left\{\frac{d}{2}+\left(\frac{T}{4}\right)\right\}^2\right]}{2\left\{\frac{(D-d)}{2}-3\left(\frac{T}{4}\right)\right\}\left\{\frac{D}{2}-\left(\frac{T}{4}\right)-D_b\right\}} \tag{7}$$

$$T = D - d - D_b \tag{8}$$

$$g_1(X) = \frac{\phi_0}{2\sin^{-1}\left(\frac{D_b}{D_m}\right)} - z + 1 \geq 0 \tag{9}$$

$$g_2(X) = 2D_b - K_{D_{min}}(D-d) \geq 0 \tag{10}$$

$$g_3(X) = K_{D_{max}}(D-d) - 2D_b \geq 0 \tag{11}$$

$$g_4(X) = \zeta B_w - D_b \leq 0 \tag{12}$$

$$g_5(X) = D_m - (0.5-e)(D+d) \geq 0 \tag{13}$$

$$g_6(X) = (0.5+e)(D+d) - D_m \geq 0 \tag{14}$$

$$g_7(X) = 0.5(D - D_m - D_b) - \varepsilon D_b \geq 0 \tag{15}$$

$$g_8(X) = 0.515 \leq f_i \leq 0.52 \tag{16}$$

$$g_9(X) = 0.515 \leq f_o \leq 0.53 \tag{17}$$

4. Multi-Objective Genetic Algorithm (MOGA)

The planned MOGA to locate non-dominated resolutions for multi-objective design optimization of wind turbine pitch bearings has been offered as:

1. Prepare the factors of MOGA.
2. Set the populace at random.
3. Calculate the appropriateness of each chromosome.
4. Accomplish the arithmetic crossover process.
5. Complete the mutation method.

6. Check the suitability of the fresh individuals.

7. Implement the ascendency test.

8. If the passable number of entities indispensable for Pareto optimal front creation is accomplished, then conclude, or continue.

9. Choose the most exceptional bargained resolution consistent with the decision maker's penchant.

5. Multi-Objective JAYA Algorithm (MOJAYAA)

MOJAYAA is a relatively novel Teaching-Learning Based Optimization (TLBO) algorithm instituted on enhanced Strength Pareto Evolutionary Algorithm and the steps of the algorithms have been presented below.

1. Prepare the population of solutions randomly.

2. Evaluate the objective functions for each solution in the population.

3. Perform non-dominated sorting to categorize the solutions into different Pareto fronts.

4. Calculate the crowding distance for each solution in a Pareto front.

5. Select solutions for the next generation based on a combination of non-dominated sorting and crowding distance.

6. Apply exploration and exploitation operators to the selected solutions.

7. Update the population with the newly generated solutions, maintaining the desired population size.

8. Check if the termination criteria are met.

9. Return the Pareto front solutions as the final set of trade-off solutions.

6. Results and Discussions

In the existing research, the optimal design limitations of pitch bearings have been investigated with the aid of MOGA along with MOJAYAA. Comparable parametric limits and restrictions have been considered for each optimization algorithm and have been shown in Table 2.

$B_w \sim \{30, 75\}$

$c_1 \sim \{0.00617, 0.0864\}$
$c_2 \sim \{0.6796, 4.06\}$
$d \sim \{325, 2988\}$
$D \sim \{495, 3675\}$
$D_b \sim \{0.15(D-d), 0.26(D-d)\}$
$D_m \sim \{0.5(D+d), 0.6(D+d)\}$
$e \sim \{0.02,0.1\}$
$f_i \sim \{0.515,0.6\}$
$f_o \sim \{0.515,0.6\}$
$K_{D_{max}} \sim \{0.6,0.7\}$
$K_{D_{min}} \sim \{0.4,0.5\}$
$l_e \sim \{24.4, 44\}$
$z \sim \{40, 280\}$
$\varepsilon \sim \{0.3,0.4\}$
$\mathfrak{h} \sim \{25,64\}$
$\kappa \sim \{0.0758, 0.4601\}$
$\zeta \sim \{0.60, 0.85\}$

Table 2 Parametric Limits

The Pareto fronts attained using MOGA have been shown in Fig. 7 and 8.

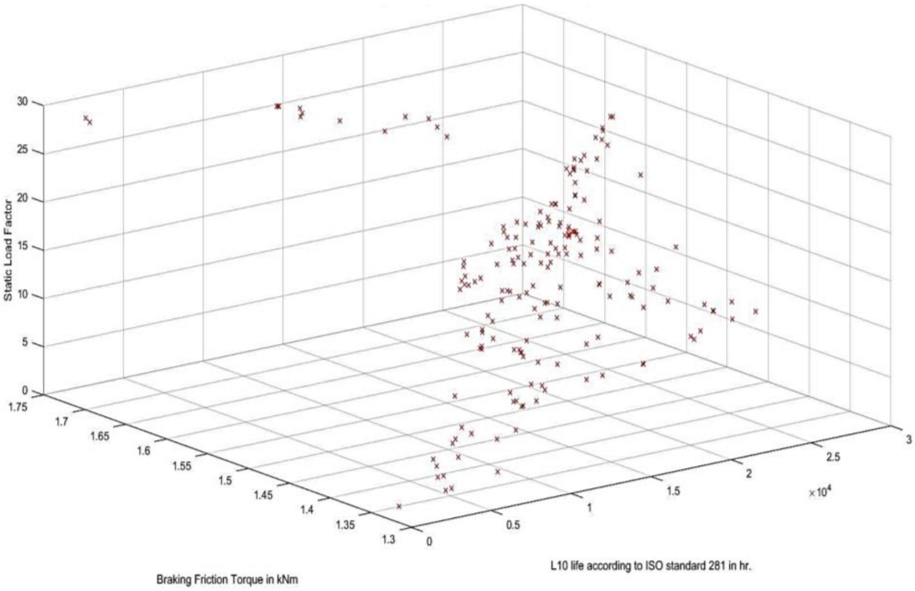

Figure 7: Pareto Front Attained by MOGA for 45° Contact Angle

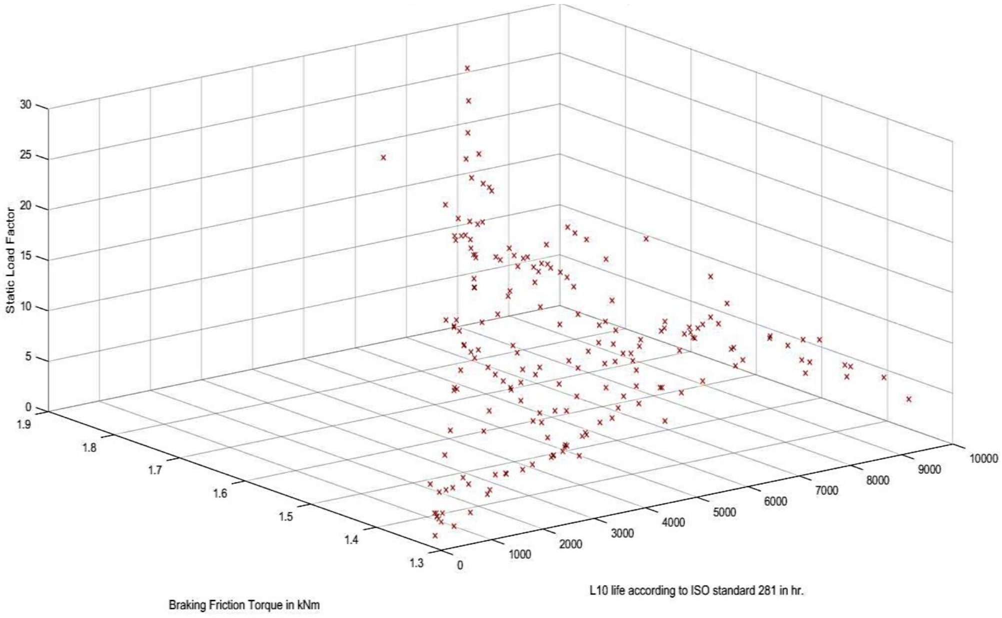

Figure 8: Pareto Front Attained by MOGA for 60° Contact Angle

The Pareto fronts attained using MOJAYAA have been shown in Fig. 9 and 10.

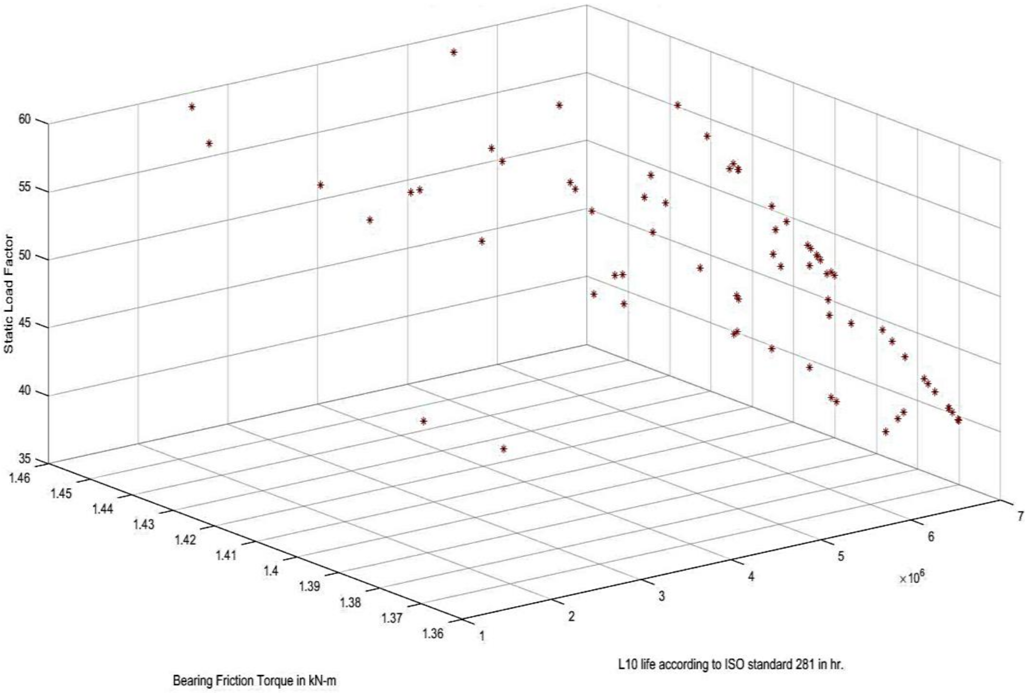

Figure 9: Pareto Front Attained by MOJAYAA for 45° Contact Angle

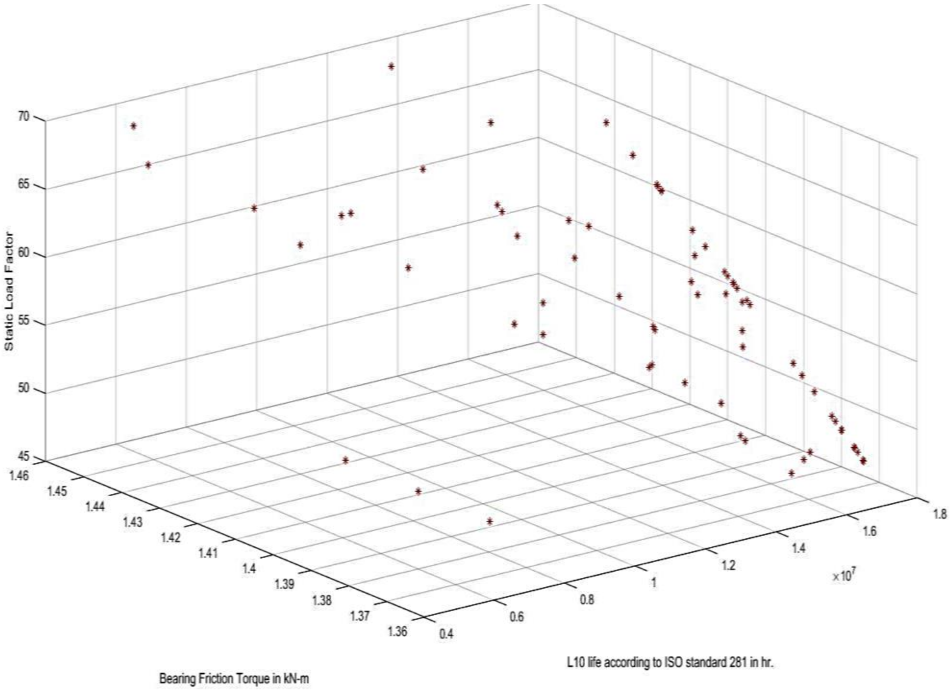

Figure 10: Pareto Front Attained by MOJAYAA for 60° Contact Angle

The optimized solutions have been presented in Table 3.

	MOGA Solution		MOJAYAA Solution	
	45^o Contact Angle	60^o Contact Angle	45^o Contact Angle	60^o Contact Angle
Maximum L_{10} Life in hr.	30000	10000	70000	180000
Minimum Bearing Friction Torque in kN-m	1.75	1.9	1.46	1.46
Maximum Static Load Factor	29	26	59	69

Table 3 Comparison of Results Attained by MOGA and MOJAYAA

The results shown in Table 3 show the superiority of MOJAYAA for optimizing the design of wind turbine pitch bearings. The improved design enhances the reliability of performance and minimizes the generation cost of wind power.

7. Conclusion

The study attempted to expand the performance of a wind power generation system by enhancing the design of pitch bearing. MOGA and MOJAYAA have been applied to optimize the considered objectives. The study confirms the efficiency of MOJAYAA over MOGA for the current research work.

6. Acknowledgement

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