Received December 23, 2020, accepted January 6, 2021, date of publication January 19, 2021, date of current version March 26, 2021.
Digital Object Identifier 10.1109/ACCESS.2021.3052899

Ceiling Fan Drives–Past, Present and Future

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This work was supported by the Stone Link Design Labs, Chennai.

ABSTRACT Major electrical gadgets are moving towards energy-efficient designs. Ceiling Fans are one of the prime focuses of such electrical gadgets. This article discusses and reviews about the past, present and future scenarios of the ceiling fans. The review includes different electric motors used in this application with its electromagnetic designs, controller developments, and mechanical designs, including Computational Fluid Dynamics (CFD) and blade structures. Present-day energy-efficient fans with their technical and performance indices are extensively discussed as a case study. In this work novel innovations are concerned for the future development of the ceiling fans. The highlights of the article: 1. The fan is one of the potential energy consumption application globally. 2. Reducing the power consumption of these fans leads to lowering the carbon-di-oxide emissions 3. A comprehensive review has been done on ceiling fans for the first time - terms of their electrical and mechanical structures. 4. Currently, available Energy efficiency fans are discussed in details with its performance. 5. Future scope to reduce power consumption is highlighted in the conclusion section.

INDEX TERMS Ceiling fan, CFD, blades, motors.

I. INTRODUCTION

Energy-efficient devices save energy consumption considerably. Reducing energy consumption led to reduces the adverse effects of global warming. In particular, the fans are one of heavily consumed electrical equipment in a country like India, around 20 to 30% of the total energy produced. Saving energy through energy-efficient products helps the countries to become energy surplus.

In 1882, Schuyler Skaats Wheeler invented the electric fan later; it was patented by Philip H. Diehl in 1889 [1]. After that, there was a massive proliferation in electric fans [2] which is clear from Fig. 1. till date. Fans are one of the most widely used appliances in tropical countries like India as they account for over 6% of primary residential energy use, making them responsible for a couple of terawatt-hour energy consumption per annum [3]. Different fans such as (i) ceiling (ii) table (iii) wall mounted (iv) pedestal etc., are available in the commercial market. Details of fan operating principle, types, laws, design, selection, requirements, and applications are found in [4].

This article indulges in revisiting the research developments that happened in fans into the ceiling fans. Section II briefs about the electric motors used in the ceiling fans with its advancements. Computational fluid dynamics play a significant role in fan energy-efficient designs, and it is thoroughly discussed in section III. Power converters, digital controllers, are concisely reproduced in section IV. Section V carefully reviewed the blade structures and noise. Existing energy efficient fans in the commercial market are discussed as a case study in section VI. Future developments and conclusions are made in section VII and VIII, respectively.

II. BASED ON ELECTRIC MOTOR [5]–[31]

Two other new high-efficiency ceiling fans with flat wooden blades are developed based on axial flux permanent magnet

The associate editor coordinating the review of this manuscript and approving it for publication was Yassine Maleh.

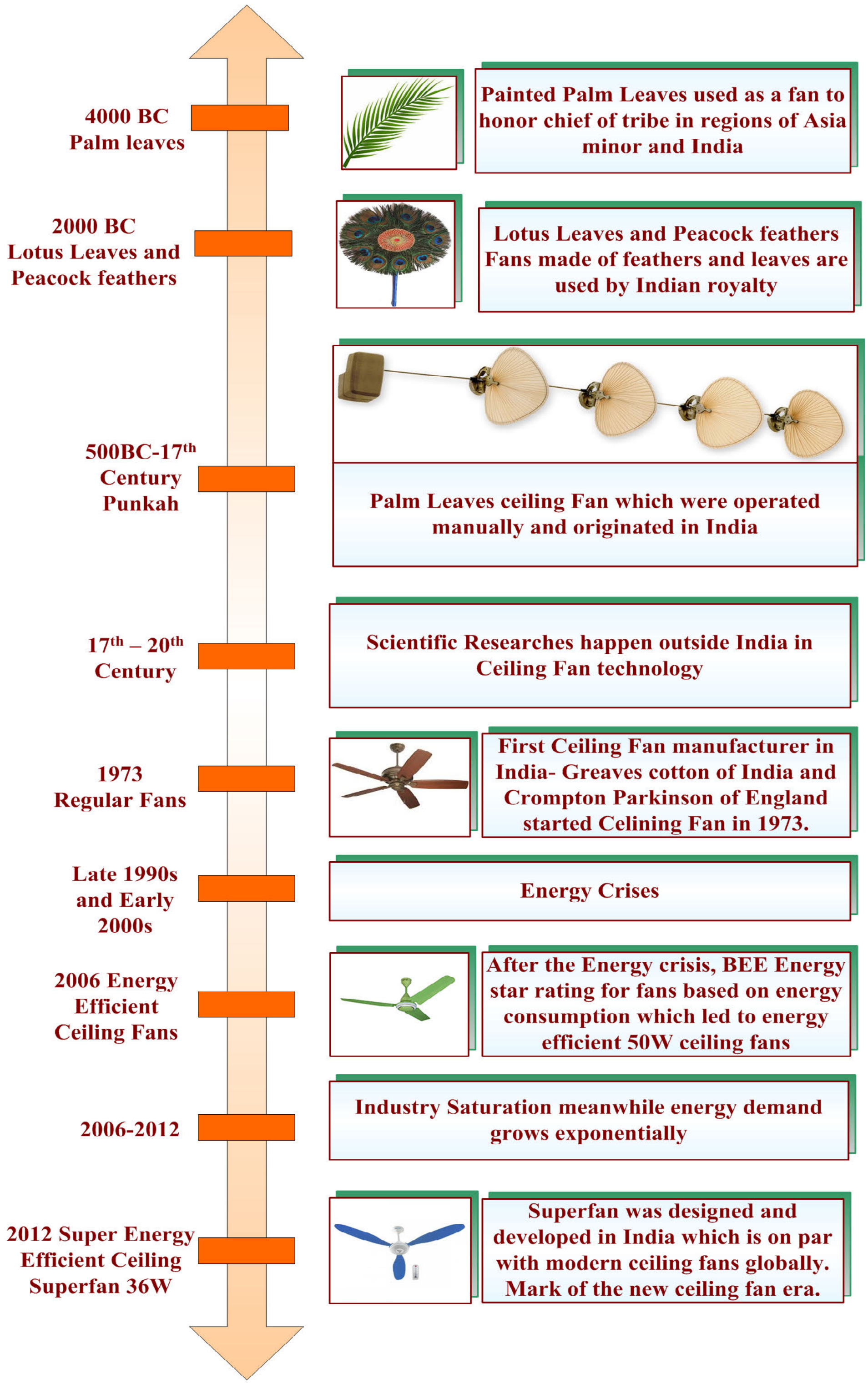

FIGURE 1. History of Ceiling Fans [2].

brushless DC motors [5]. Those motors are highly efficient, are maintenance-free, lower noise and are driven by commutation and control electronics from the mains (refer Fig. 2).

A 30W (input power), 48V, 310rpm outer rotating Permanent Magnet Brushless DC (PMBLDC) motor for an energy-efficient ceiling fan [6] had been designed and validated through the computer-aided platform. The variation

TABLE 1. Three and Four Blade Fan Performances with 9, 12 & 24 VDC Power Supply.

Fan Type	9V, 3 blade	9V, 4 blade	12V, 3 blade	12V, 4 blade	24V, 3 blade	24V, 4 blade
Average Velocity (m/s)	0.19	0.22	0.32	0.32	0.61	0.56
Maximum Velocity (m/s)	0.90	0.84	1.37	1.14	1.81	1.69
Total CFM	852	1221	1476	1820	3925	3600
Total l/s	402	576	697	859	1853	1699
Total Watts	1.62	1.69	4.09	4.11	12.9	14.6
RPM	75	66	102	83	138	117

FIGURE 2. High efficiency ceiling fan [5].

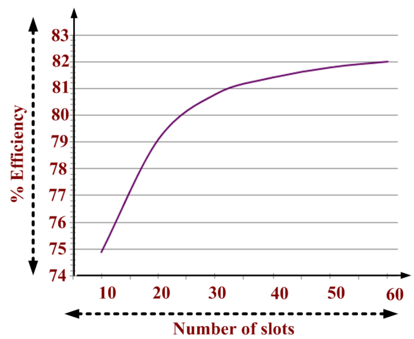

FIGURE 3. % Efficiency Vs. Variation of Number of Slots.

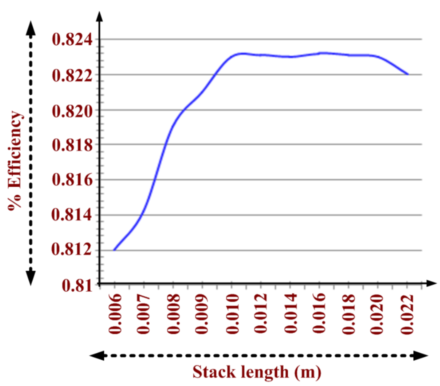

FIGURE 4. % Efficiency Vs. Variation of Stack Length.

of efficiency to (i) stack length, (ii) number of stator slots and (iii) number of poles are analyzed through the finite element analysis (FEA) (Figs. 3 - 5).

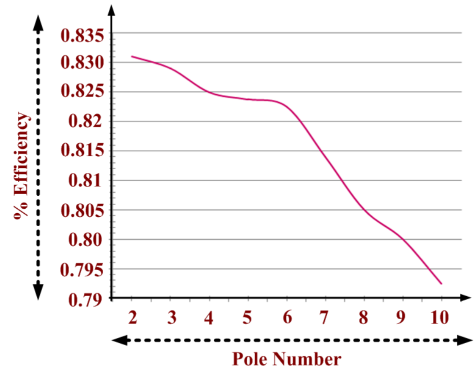

FIGURE 5. % Efficiency Vs. Variation of Number of Poles.

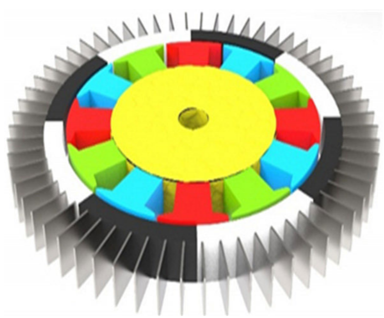

FIGURE 6. Cross Section of PMBLDC.

A study was undertaken to test the extent of air gap variation when components are produced as per design [7]. The findings suggested, shifting the rotor and covering spigot machining operation to newer machines with better process capability to reduce variation. In 2002, Gossamer Wind Solar Powered (GWSP) ceiling fans [8] were developed. Table 1. provides the performance summary of 3 and 4 blade designs, whereas Table 2. shows the performance of the three-blade fan connected to the 25 watt and 10-watt PV panels. With the reduced cost and improved performance [9], a 110 Volt PMBLDC motor (shown in Fig. 6) has been designed and tested for the speed range between 90 – 200 rpm.

The designed motor is having an 8 pole, 12 slots on the stator. The tested PMBLDC motor saves around 50% of energy consumption compared to the conventional single-phase induction motor (SPIM) as clear from Fig. 7.

TABLE 2. PV Powered Fan Performance.

Year	2016	2020	2030	2012-2016	2012-2020	2012-2030
Australia	0.06	0.12	0.21	0.12	0.50	2.31
Brazil	1.43	3.35	6.09	3.29	13.83	65.41
Canada	0.05	0.11	0.19	0.11	0.46	2.08
China	9.01	20.68	35.77	21.02	86.50	396.59
EU	0.48	1.08	1.76	1.14	4.59	20.22
India	14.17	33.54	62.38	32.52	137.91	660.60
Indonesia	1.12	2.63	4.81	2.59	10.88	51.51
Japan	0.24	0.54	0.84	0.56	2.27	9.90
Korea	0.11	0.26	0.44	0.26	1.07	4.91
Mexico	0.41	0.93	1.53	0.96	3.90	17.43
Russia	0.15	0.34	0.52	0.37	1.46	6.19
South Africa	0.17	0.40	0.65	0.40	1.67	7.46
US	2.43	5.65	9.86	5.61	23.47	108.57
Total	29.82	69.62	125.05	68.94	288.51	1353.19

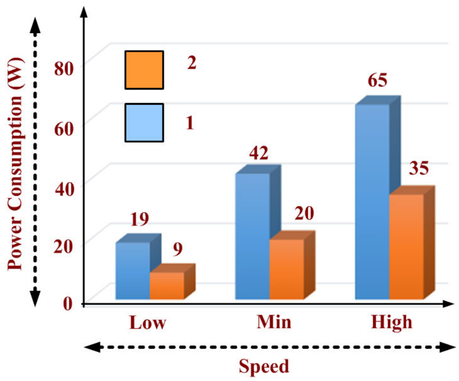

FIGURE 7. SPIM Vs. BLDC.

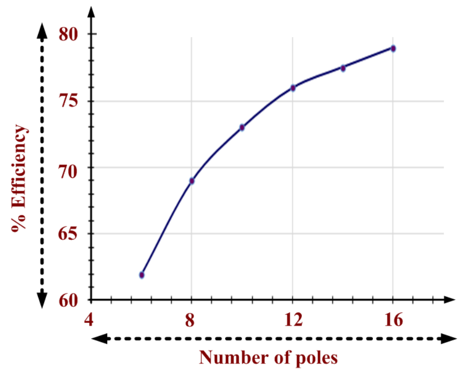

FIGURE 9. % Efficiency Vs. number of poles for single phase PMBLDC motors.

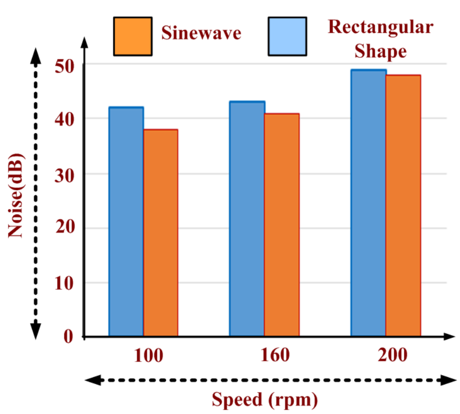

FIGURE 8. Noise at Different Speeds for PMBLDC motors [11].

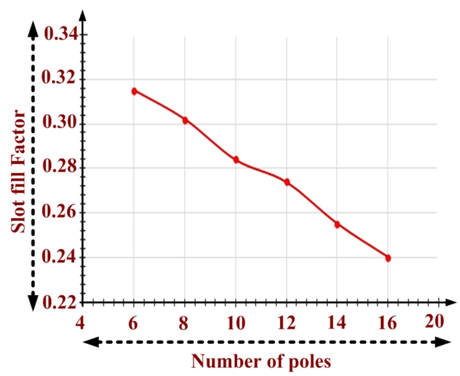

FIGURE 10. Slot fill factor Vs. number of poles.

Further, the cogging torque of PMBLDC and hence the noise (Fig. 8) have been reduced [9]–[11] by using the sine back EMF voltage with the sine waveform currents.

Single-phase PMBLDC motors are cost-effective and easy to manufacture. One such motor drive [12] for 170 V, 20 W, 360 rpm, had been designed and tested. Sensitivity analysis on the number of Poles, slot fill factor and starting torque (Figs. 9 - 11) are discussed to optimize the designed motor.

If PMBLDC motors are implemented in all ceiling fans sold by 2020, 70 Terawatt hours per year could be saved and 25 million metric tons of carbon dioxide equivalent emissions per year could be avoided, globally [13]. Table 3 shows the results of the energy savings potential analysis in 2016, 2020, and 2030 with the use of high efficient BLDC motors.

TABLE 3. Annual and Cumulative energy Savings forecasts [14].

Year	2016	2020	2030	2012-2016	2012-2020	2012-2030
Australia	0.06	0.12	0.21	0.12	0.50	2.31
Brazil	1.43	3.35	6.09	3.29	13.83	65.41
Canada	0.05	0.11	0.19	0.11	0.46	2.08
China	9.01	20.68	35.77	21.02	86.50	396.59
EU	0.48	1.08	1.76	1.14	4.59	20.22
India	14.17	33.54	62.38	32.52	137.91	660.60
Indonesia	1.12	2.63	4.81	2.59	10.88	51.51
Japan	0.24	0.54	0.84	0.56	2.27	9.90
Korea	0.11	0.26	0.44	0.26	1.07	4.91
Mexico	0.41	0.93	1.53	0.96	3.90	17.43
Russia	0.15	0.34	0.52	0.37	1.46	6.19
South Africa	0.17	0.40	0.65	0.40	1.67	7.46
US	2.43	5.65	9.86	5.61	23.47	108.57
Total	29.82	69.62	125.05	68.94	288.51	1353.19

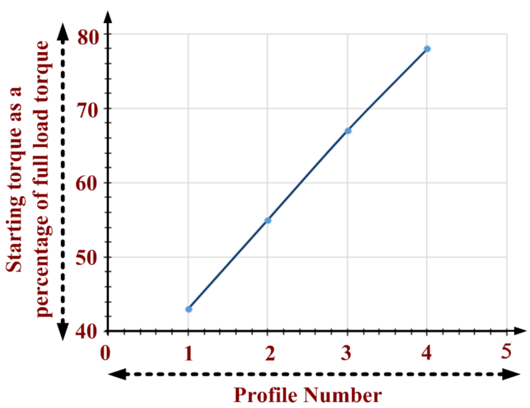

FIGURE 11. Starting Torque Vs. air gap profile number.

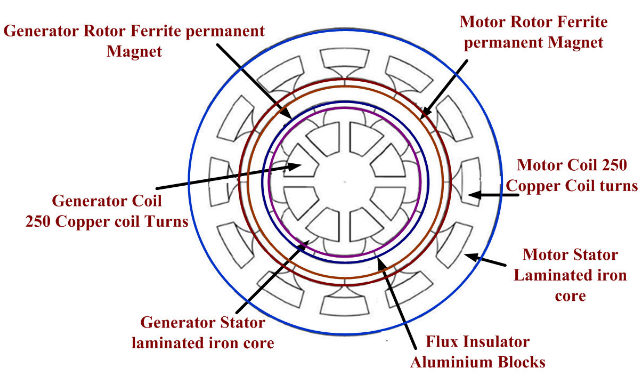

FIGURE 12. Machine Cross section [15], [16].

A ceiling fan capable of harnessing wasted kinetic energy from a ceiling fan blade's rotation converted to the energy back to electricity had been examined in [14], [15]. The designed electrical machine has two parts (refer to Fig. 12). One is a motor, and another is a generator. Detailed simulation results and its optimization based on different split and pole pitch ratio [15] show that the designed electrical machine is prominent in high-efficiency ceiling fans.

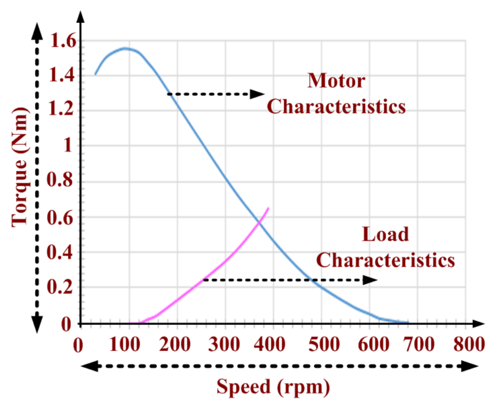

FIGURE 13. Torque – Speed characteristic of ceiling fan and load curve.

Three-phase PMBLDC motor for ceiling fan using bonded Neodymium Iron Boron (NdFeB) and ferrite magnets are designed in [16]. The intersection point (Fig. 13) is the motor's operating point in the load curve. To reduce the rotor's back-iron thickness, the magnet's Halbach arrangement was used to magnetize it. The findings inferred that the total weights of active materials in bonded magnet motor and ferrite are 0.884kg (47.2% more) and 1.302kg respectively, but the overall cost in ferrite motor was Rs.338 (22.1% less) compared to Rs.434 in case of bonded magnet motor. The author of [17] designed two different techniques (i) centre of the outer arc of the stator teeth is offset from the center of the cross-section of the fan shaft in the radially outward direction and (ii) rotor Magnet skewing (Fig. 14), to reduce the cogging torque and noise.

With an offset value of 35mm, peak cogging torque is 0.05 N-m which is 8.8% of the rated torque, whereas for a magnet skewing of 3.75 degrees it is 0.005 N-m (Fig. 15) which was only 0.88% of the rated torque. Further, the stator with pole shaping structure reduced the motor's overall noise by 7.1 dB on testing.

A method of generating power by a ceiling fan and its use in a battery for powering low power electrical gadgets are

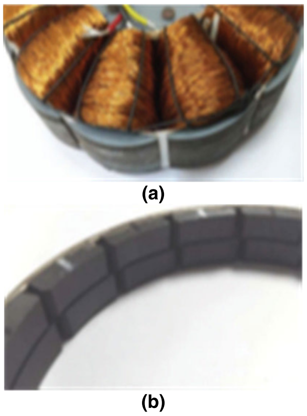

FIGURE 14. (a) Stator with centre of teeth arc offset by 35mm (b) PM skewed by 3.75 degrees.

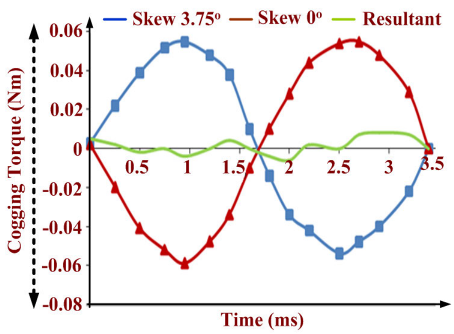

FIGURE 15. Cogging torque Vs. time.

discussed in [18]–[23]. The advantages of those designs are (i) reduction of carbon-di-oxide (ii) many electrical and electronic devices can be operated on situations like electricity failure. Ceiling fans use SPIM, Universal motor (rarely) or PMBLDC motor.

The performance of these motors is compared [24] based on its accounts. The TRIAC control has got the variation of speed in the induction motor, whereas in BLDC it is by either changing the supply voltage firing angle.

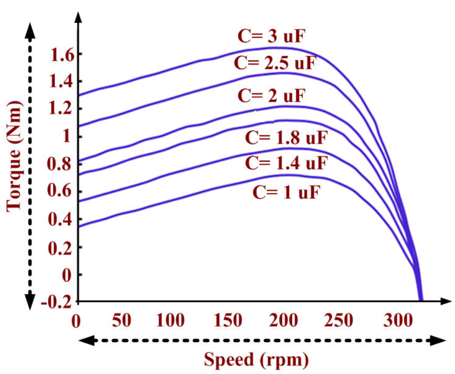

FIGURE 16. Torque vs. Capacitor values [26].

Different capacitor values, winding turn ratio and impedance ratio, are analyzed based on two-dimensional finite element analysis to optimize the permanent split-capacitor single-phase induction motor [25]. Based on the Equivalent circuit developed, the parameters of the designed motor are fine-tuned for the required output. It is clear from the results (Fig. 16) that higher value of capacitor would make the starting torque higher and the operating slip smaller at similarly rated load.

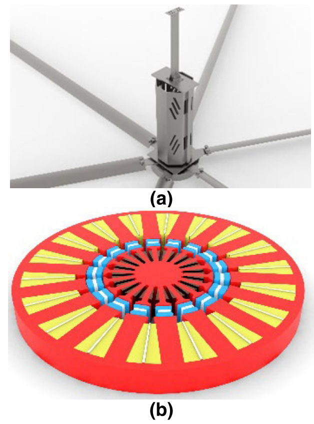

FIGURE 17. (a) Monstrous fan (b) DSSR-BLDC.

PMBLDC motor with Double Stator Slotted Rotor Brushless DC Motor (DSSR-BLDC) with a speed range of 50-200 rpm for monstrous fan application was developed in [26]–[28] (Fig. 17).

The development of five-phase BLDC has a strong potential to revolutionize motor technology in an energy-efficient fan [29]. Five phase BLDC motors divide the requisite power among multiple phases thus allowing higher power levels, increasing the frequency of torque pulse rate, reducing per phase rotor current without an increase in the per phase voltage, and subsequently increasing performance power concentration on each phase. The power consumed by this BLDC is only 25 Watts.

Electrolytic capacitor-less, induction motor drive system for domestic fan application has been developed in [30]. V/F control was adapted to vary the speed of the fan.

Efficiency improvement in the SPIM has been improved by considering the critical parameters such as B-H characteristics, loss/weight of the magnetic material (steel), number of turns in stator and rotor turns, stack length, and capacitor value and the blade characteristics [31]. The optimal design was got using a dual-layer of design of experiment Fig. 18.

III. BASED ON CFD [32]–[45]

Computational Fluid Dynamics (CFD) simulation is useful in predicting the airflow around a ceiling fan. One such article [32] provides us with the insight into the airflow of a ceiling fan modeled as boundary conditions of air velocity data measured near the ceiling fan. Matsushita Electric Industrial, FM131H-W fan, was used in this study. Fig. 19 shows the schematic diagram of the airflow model of the chosen ceiling fan.

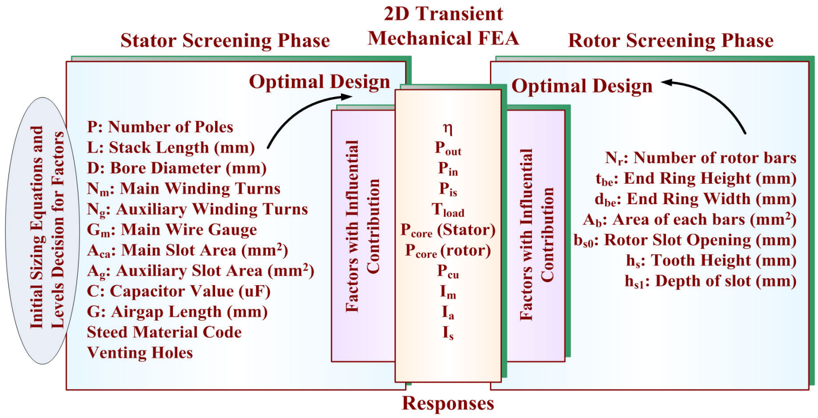

FIGURE 18. Overall Process of Design.

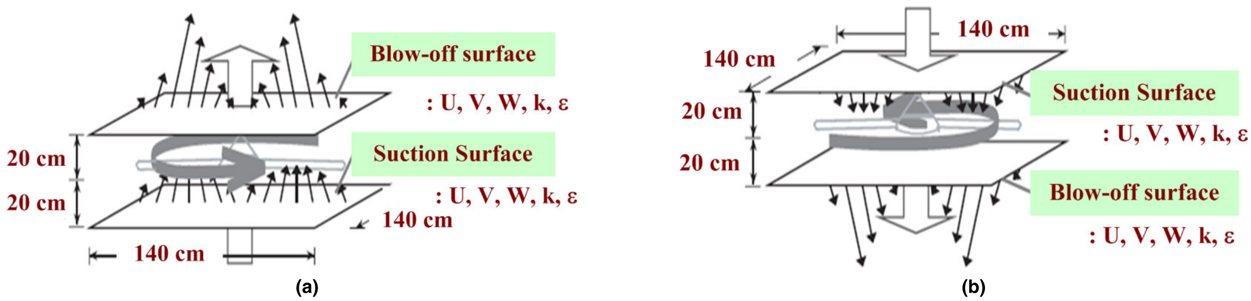

FIGURE 19. Schematic of airflow model [33], (a) Upward airflow direction, (b) downward airflow direction.

The experimental setup was developed to measure each air velocity's average value using three-dimensional ultrasonic anemometer (KAIJO, WA-590) and hot-wire anemometer of constant temperature type (KANOMAX JAPAN, 0251 R-T5) at different frequencies.

Flow-induced by the operation of a ceiling fan in a room has been studied [33]. Significant performance improvements are got by introducing winglets or spikes at blade tips, because of the disruption of tip vortex activity (Fig. 20).

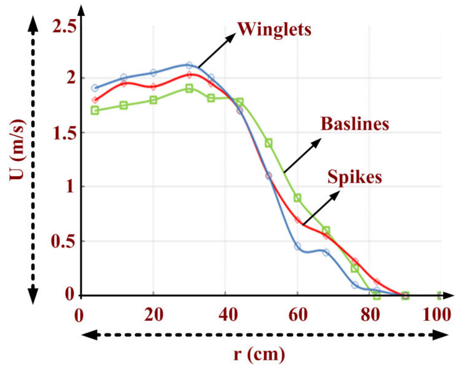

FIGURE 20. Effect of the addition of winglets and spikes.

To find the difference in air velocity variations for the ceiling fan operating at the constant speed mode and the variable speed mode, a measuring point at the half of the blade length and 100 cm down from the fan blades was chosen to represent the flow characteristics [34]. An analytical and a CFD model was used to predict the flow pattern induced by a ceiling fan into a selected space [35], [36]. The findings inferred that increasing the fan rotational speed results in increasing the local downward velocity distribution inside the area. Hence, operating a ceiling-fan at an improper rotational-speed may cause disturbance for occupants.

Numerical modeling in [37]–[40], used steady-state CFD with a rotating reference frame to simulate fan blades' rotation. The developed numerical model reduced the simulation cost, properly characterized the fan-induced airflow, reproduced the effects of ceiling fans and ultraviolet germicidal irradiation (UR-UVGI) fixtures on the indoor environment, and should aid in the impact's investigation of ceiling fans on UR-UVGI disinfection efficacy.

A transient three-dimensional CFD implicit model of a ceiling fan has been found in [39], [41]–[43]. The model developed can accurately, qualitatively and quantitatively, predict the airflow generated by a typical Indian ceiling fan in a room.

In [44], [45] by changing the ceiling fan parameters, the influence of the airflow is investigated by practical measurement of human body temperature. Based on the simulation studies, it was found that (i) the air velocity is reduced as the air approaches the floor, (ii) the thermal plume that is generated by the human body is affected by a downward airflow at a velocity of 0.3 m/s, (iii) optimal thermal comfort can be achieved for the human body if the air velocity is 1.34 m/s when the airflow reaches the top of the head.

IV. BASED ON POWER CONTROLLERS [46]–[65]

Through compliant wrists, automatic inspecting and monitoring techniques, the assembly line of a ceiling fan was provided with better reliability, safety and adaptability to variation of product sizes [46]. Much similar to the previous literature, a computer monitoring and control system of the robotic & assembly line for ceiling fan motor has been described in [47].

Utilization of a conventional load-commutated inverter for a ceiling fan can be found in [48]. Optimizing the commutation angle [49] for one operating point leads to reduced current, power consumption and temperature, and by increases the efficiency and the lifetime of the PMBLDC motor.

A practical implementation of PMBLDC motor [50], [51] and its complete electronics such as SMPS and controller reveal India's potential for energy savings. The power supply unit in this article was based on the offline flyback converter using the TOP261EN. Further, a comparison between the developed BLDC and conventional 42" ceiling fans (Fig. 21) were discussed. PMBLDC motor with three different speed control method is highlighted in [52], [53].

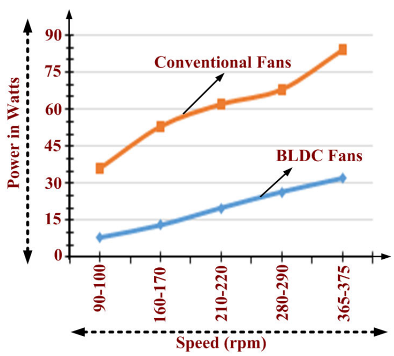

FIGURE 21. Comparison between BLDC fan and Conventional fan.

During, it is manual mode speed can be controlled by a potentiometer. If it is the auto mode, the speed is automatically changed depending on the room temperature using LM35 temperature sensor. If remote control mode is selected, the speed can be adjusted by using a remote controller through an RF module (refer Fig. 22).

Buck-Boost converter (Fig. 23) had been developed because of a smaller number of passive components and fewest losses in the DC-DC converter for a 120V PMBLDC motor. Experimental results show that the developed converter reduces the THD and significantly improves the power factor [54].

Sinusoidal and square wave signals applied to a PMBLDC motor are individually applied to the motor, and characteristics are studied in [55]. Based on the test results, Square wave mode operation provides better torque, improved power factor, quick settling time, lesser current ripples, harmonic content and voltage distortion when compared with the sine wave motor. Microcontroller (PIC16F877A) based speed control technique [56]–[59] has been implemented to control a ceiling fan's speed. Based on the temperature variations, the speed of the fan was alerted.

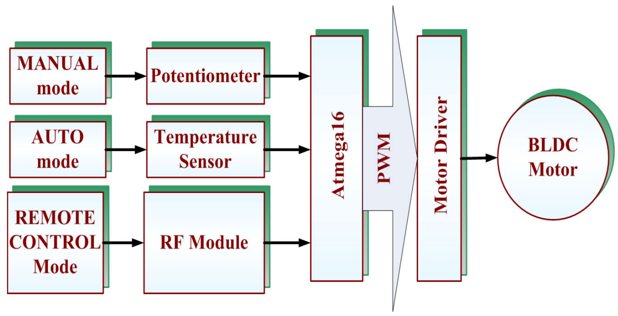

FIGURE 22. Functional Block Diagram.

Implementation of the PMBLDC outer rotor motor control algorithm using FPGA (Field Programmable Gate Array) has been found in [60]. The developed algorithm makes the ceiling fan motor's rotor speed controlled within ± 2rpm speed error in the steady-state condition. Automation has become one of the fundamental interests in modern-day technology [61]–[64]. An alternative smart fan (Internet of Things (IoT) based) from a comfort and cost perspectives point has been discussed in [61]. The significant advantage of this method of control is that the user can control the speed of the fan via the smartphone, and hence, the fan motor can be efficiently controlled by using a Wi-Fi connection. Zeta converter fed BLDC motor with fuzzy control and boost converter fed BLDC motor with a PI controller tested for a ceiling fan motor [65]. Based on the experimentation, zeta converter and fuzzy logic were superior based on torque, power factor and speed.

V. BASED ON BLADE DESIGN, NOISE, VIBRATION AND TESTING [66]–[68], [68], [70]–[92], [92]

Larger fan blades are recommended to increase airflow. The authors of [66] estimated the combined motor and fan efficiencies at less than 5%. The design objective in [67], [68] was a fan producing air flows of 2 meters per second across the blade radius at a speed of 150 - 200 rpm with lower noise. The performance of the chosen fans (Emerson, Hunter Summer Breeze, and Ceiling Fan-1 (CF-I)) such as input power consumption (Watts), air velocity (cubic feet per minute, CFM) and efficiency index otherwise called as Service value (CFM/Watts) are compared. Further, the authors developed a light-weight and highly durable prototype blade that comprises a foam core material. Matching between the motor and the rotor blades delivers higher efficacy in a ceiling fan [69]. Three ceiling fan models (Bajaj, Orient and Khaitan) are studied to measure the system efficacy as per the Bureau of Indian Standards (BIS). The study further inferred that the

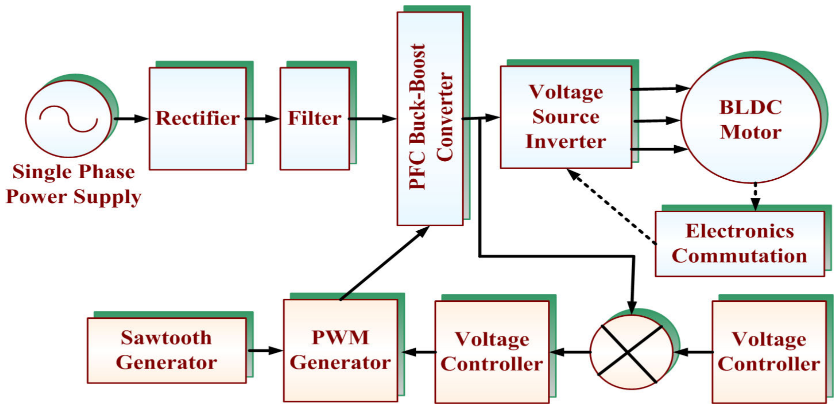

FIGURE 23. Power Electronics for Fan using Buck-Boost converter.

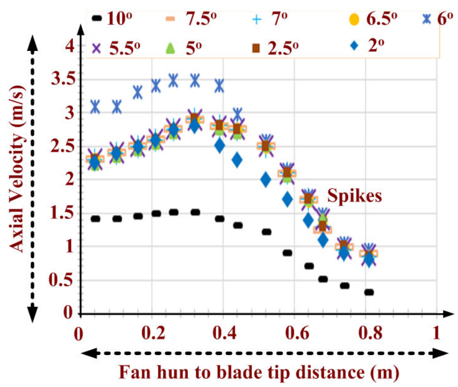

FIGURE 24. Variation of axial velocity Vs. distance.

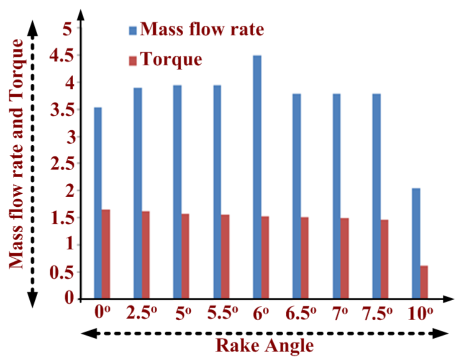

FIGURE 25. Mass Flow rate and Torque Vs. Rake angle.

change in blade angle and the slip have a more significant impact on motor efficiency. A survey of the development of an enhanced ceiling fan, detailing the engineering design process, highlighting health, safety, and environmental can be found in [70]. In [71], performing the Star Co. Fan super deluxe model had been studied. Specific cases of rake angles (00– 100) compared to axial velocity, mass flow rate, air delivery, torque and service value are considered and compared extensively (Figs. 24 - 26). The study concluded that the six-degree rake angle shows enhanced performance.

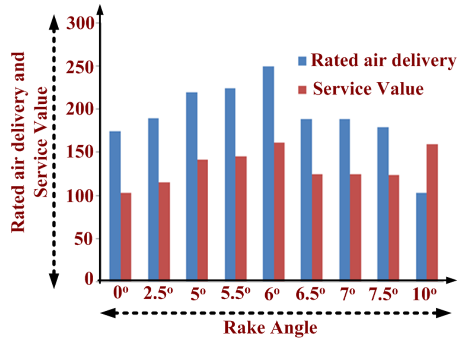

FIGURE 26. Rated Air Delivery and Service Value Vs. Rake angle.

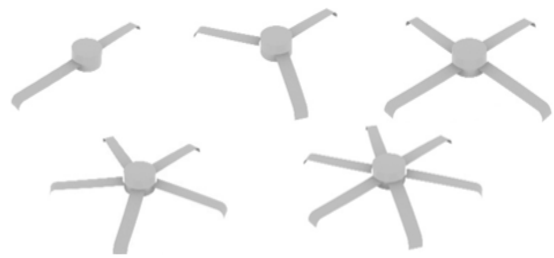

FIGURE 27. Ceiling fans with varying number of blades.

In [72]–[75] response surface method (RSM) had been adopted to predict the noise characteristics of a fan. The results show the ceiling fan noise minimized by operating the fan at the room size 3 level, rod length 3 levels, and the knob position at level 1.

In [76]–[79] the effects of forwarding elliptic sweep angle, tip width, root and tip angle of attack are analyzed. Reference [80] Provides both technical and economic analysis of efficiency improvement options. Despite the massive saving potential, financial incentive programs such as the Super-Efficient Equipment Program (SEEP) for fans in India that promote the adoption of highly efficient fans is the need of the hour. In [81], the effects of the number of blades on the fan performance (Fig. 27) were discussed.

It was clear from Fig. 28 that increasing the number of blades Volumetric flow rate, Mass flow rate, and torque

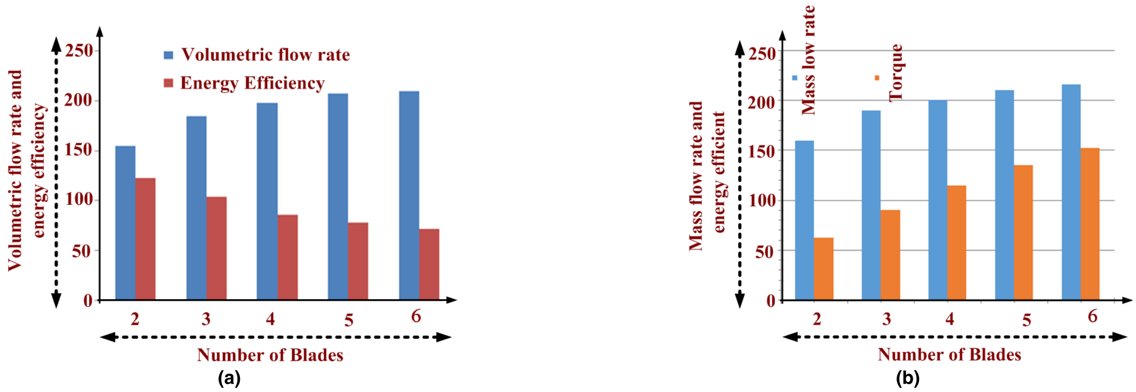

FIGURE 28. Impact of number of blades on (a) volumetric flow rate and energy efficiency, b) Mass flow rate and Torque.

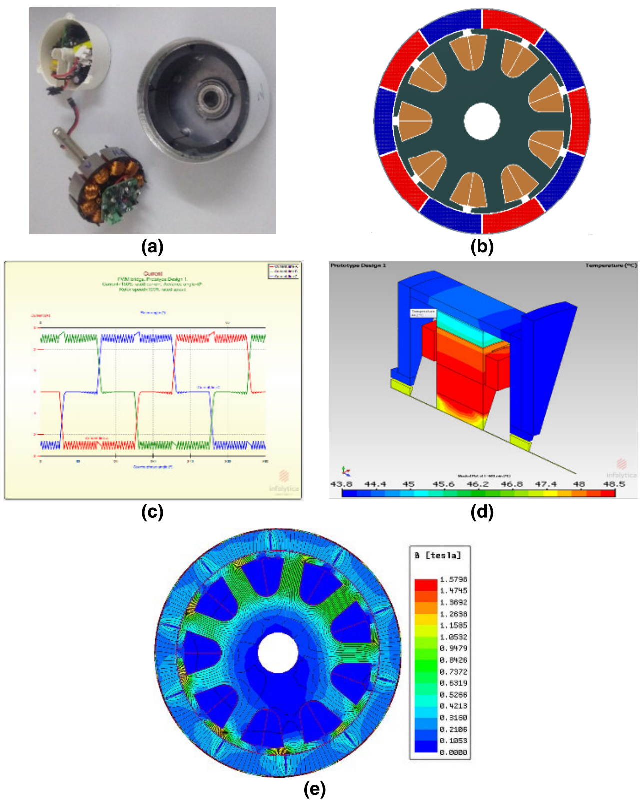

FIGURE 29. Atomberg Gorilla Renessa., a) Dismantled motor, b) CAD model, c) Phase currents, d) Temperature plot e) Magnetic Flux density plot.

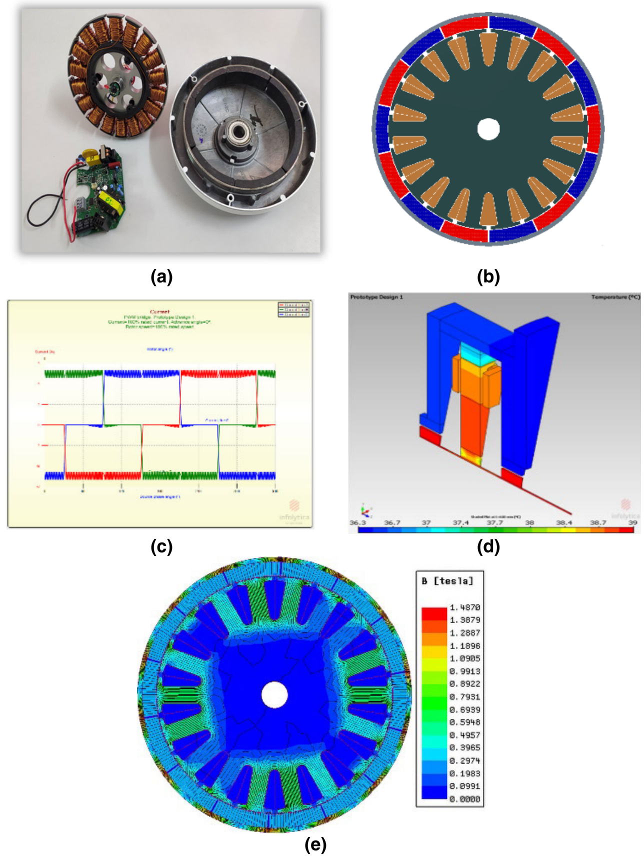

FIGURE 30. Atomberg Gorilla Version – 2, a) Dismantled motor, b) CAD model, c) Phase currents, d) Temperature plot, e) Magnetic Flux density plot.

developed by the fan increases, whereas the energy efficiency decreases.

Ceiling fan with cooling blades is developed by [82]. It will be the better replacement of air conditioners and air coolers. Optimize the fan blade angle provides reduced energy consumption [83]. Various blade angles (0, 4, 8 and 12.5 degrees) following room conditions are analyzed and tabulated in Table 4.

By changing both swiveling and tilting of the ceiling fan down-rod, the fan can regulate airflow only in areas where we need airflow [84]. The significant advantage is that the threaded link mechanism makes it easy to maintain the ceiling fan at a specific angle, with the help of a simple geared DC motor. A sample of 200 consumers of electric fans has been taken to understand the behavior of the fan [85]. Questionnaires are based on the (i) brands, (ii) cost (iii) longevity (iv) service availability, etc. It has been concluded that most of the customers are using a specific brand for a very long period, and the price is the most crucial attribute.

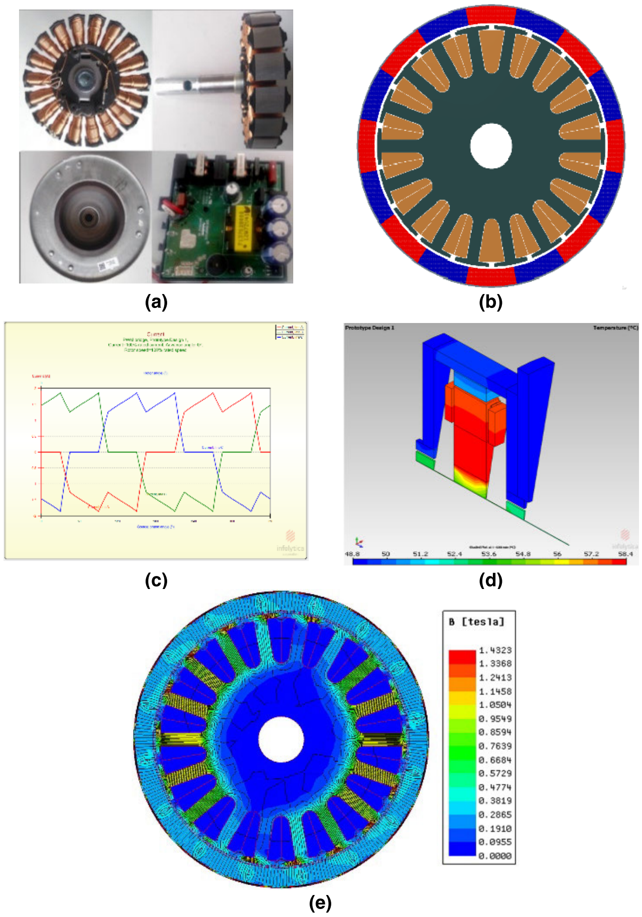

FIGURE 31. Usha (Nidec Motors)., a) Dismantled motor, b) CAD model, c) Phase currents, d) Temperature plot, e) Magnetic Flux density plot.

TABLE 4. Effect of Blade Angle.

No	Blade Angle	Average Velocity
1	0 deg.	0.07416 m/s
2	4 deg.	0.081464 m/s
3	8 deg.	1.040091 m/s
4	12.5 deg.	0.071432 m/s

A multi-axis ceiling fan [86], [87] has been developed which covers larger air delivery area compare to the conventional ceiling fan. It comprises a gear mechanism and AC & DC motor. The significant advantage of the designed fan is that it will rotate about over one axis. With the help of a 54-inch Fan, the influence upon the measured volume of air of (a) Distance of plane of observation below fan blades (b) Position of fan in, and size of, room (c) Height of fan above floor (d) Distance between fan and ceiling (e) Room temperature and (f) Speed of fan were determined [88]. Results got by [88] are discussed critically by [89].

A comparative lab test of 1400 mm (56'') ceiling fan of regular models category and its findings are available in [90], [91]. They are testing the fans mainly focused on three parameters: safety, performance and energy. Ten brands are chosen for this test. Fan faults can be classified as

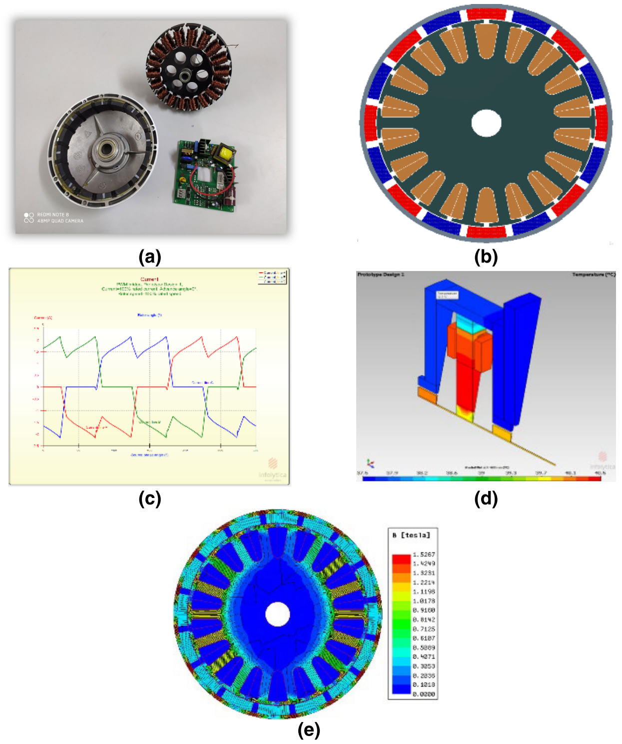

FIGURE 32. Versa., a) Dismantled motor, b) CAD model, c) Phase currents, d) Temperature plot, e) Magnetic Flux density plot.

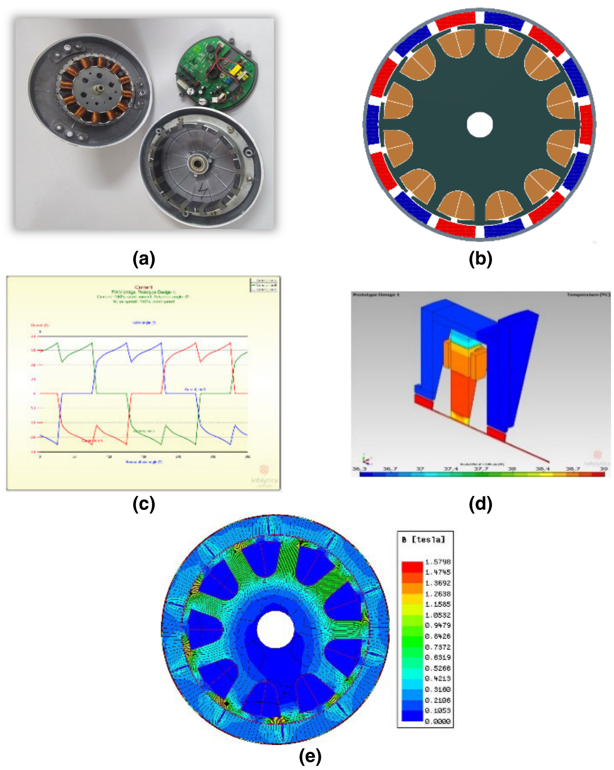

FIGURE 33. Surya, a) Dismantled motor, b) CAD model, c) Phase currents, d) Temperature plot, e) Magnetic Flux density plot.

TABLE 5. Designed Specifications.

Parameters	Units	Designed Values						
		Atomberg Gorilla Renessa	Atomberg Gorilla Version-2	Usha (Nidec)	Versa	Surya	Panasonic	Haiku
DC Voltage	Volts	24	24	24	24	120	120	12
Input Power	Watts	28	28	32	35	32	30	35
Rated Speed	RPM	350	350	375	385	360	380	177
Rotor OD	mm	102.88	155.2	116	152.37	147.9	115.54	175.3
Stator OD	mm	84	132.97	98.7	131.58	127.62	98.05	162.1
Rotor ID	mm	85	133.97	100.7	132.58	128.62	99.05	163.9
Stack length	mm	22.27	13.45	18.5	12.23	17.48	15.47	16.66
Magnet Thickness	mm	8.4	7.91	7	7	7.31	5.91	4.56
Magnet Length	mm	27.13	20.8	34.58	22.01	27.97	25.56	21.34

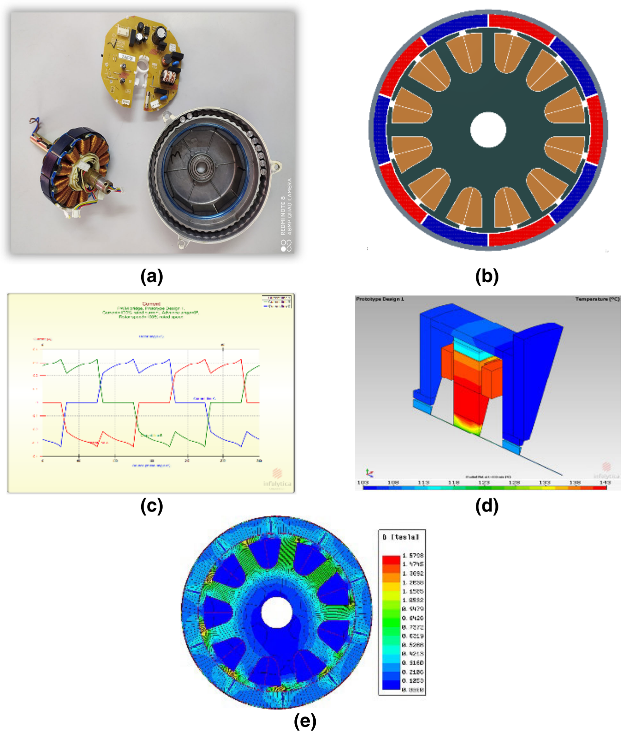

FIGURE 34. Panasonic, a) Dismantled motor, b) CAD model, c) Phase currents, d) Temperature plot, e) Magnetic Flux density plot.

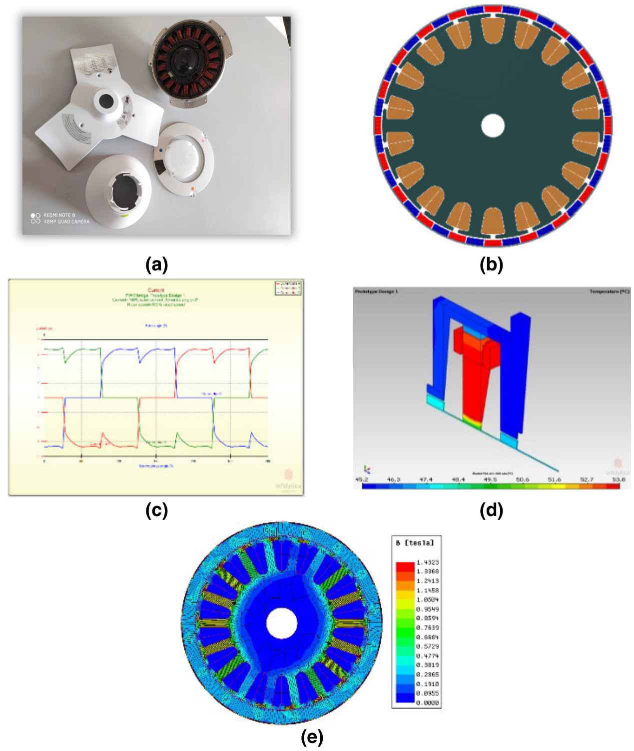

FIGURE 35. Haiku, a) Dismantled motor, b) CAD model, c) Phase currents, d) Temperature plot, e) Magnetic Flux density plot.

(i) electrical faults (winding faults) and (ii) mechanical faults (broken rotor bars, eccentricity, bearing faults). An intelligent test bench [92] based on Artificial Neural Network (ANN) with the help of online current, voltage, rpm and temperature had been developed to estimate the temperature rise.

VI. EXISTING ENERGY EFFICIENT FANS – A CASE STUDY [93]–[98]

Seven types of energy-efficient fans as:

1) Atomberg Gorilla Renessa
2) Atomberg Gorilla Version-2
3) Usha (iv) Versa (v) Surya (vi) Panasonic and
4) (vii) Haiku are bought for this case study [93]–[98].

The bought fans are first tested and then dismantled to get the dimensions of the active parts. After acquiring the required dimensions, CAD software's are used to design the same and export it to the FEA platform. Fig. 29 to 35 show the FEA results like phase current, induced emf, temperature, magnetic flux density etc., of each fan one by one. The design specification of each type is given in Table 5, and the performance, weight, and cost comparison based on the numerical study is shown in Table 6.

A. ATOMBERG GORILLA RENESSA

See Figure 29.

TABLE 6. Performance, Weight, and Cost Comparison Based on Numerical Study*.

Parameters	Units	Atomberg Gorilla Renessa	Atomberg Gorilla Version-2	Nidec (Usha)	Versa	Surya	Panasonic	Haiku
PERFORMANCE								
Current	Amps	2.04	2.04	1.25	1.39	0.236	0.223	2.59
Input Power	Watts	28.1	28	31.3	35.2	32	30	35.6
Output Power	Watts	19.4	21	24.6	29.2	24.4	22.8	15.7
Efficiency	%	69	74.8	78.7	82.9	76.2	76.1	44.2
Rotor OD	mm	102.88	155.2	116	152.37	147.9	115.54	175.3
Rotor ID	mm	85	133.97	100.7	132.58	128.62	99.05	163.9
Air Gap	mm	0.5	0.5	1	0.5	0.5	0.5	0.9
No of turns Per coil		70	32	68	62	365	512	39
WEIGHT								
Stator Core	grams	573	1040	661	822	1140	507	1960
Rotor Core	grams	29.6	133	33.3	127	142	98.3	79.5
Stator Winding	grams	256	179	285	325	204	226	206
Magnet	grams	261	226	215	155	218	144	285
Total	kg	1.12	1.58	1.19	1.43	1.7	0.976	2.53
COST								
Stator	Rs.	143.25	260	165.25	205.5	285	126.75	490
Rotor	Rs.	7.4	33.25	8.325	31.75	35.5	24.575	19.875
Winding	Rs.	200.1	139.9	222.9	254	163.5	181.2	161.2
Magnet	Rs.	391.5	339	322.5	232.5	327	216	2280
Magnet Used	Type	Ceramic	Ceramic	Ceramic	Ceramic	Ceramic	Ceramic	N52
Total	Rs.	742.3	772.2	719.1	723.8	811.1	548.5	2951

*Unintentional errors may possible

B. ATOMBERG GORILLA VERSION – 2
See Figure 30 and Table 4.

C. USHA (NIDEC)
See Figure 31.

D. VERSA
See Figure 32.

E. SURYA
See Figure 33.

F. PANASONIC
See Figure 34.

G. HAIKU
See Figure 35.

VII. FUTURE TECHNOLOGIES
This section explores the novel technologies in electric motors, power controllers and mechanical designs which can be adopted for the future.

1. Regarding electric motors, single-phase induction and Permanent Magnet Brushless DC Motors are widely used in ceiling fan application. PMBLDC motors specifically are preferred for energy-efficient fans. Switched Reluctance Motors (SRM) [99], Synchronous Reluctance Motors (with or without magnets), Flux Switching Motors (FSM) (with or without Permanent Magnets), Axial flux PM motors are the potential candidates for the energy-efficient fans in expectations.
2. Motor material and structure on the magnetic field
3. Single switch converters, improved power factor correction circuits, low on-state loss power devices, sensor-less control are some of the potential innovation in energy-efficient fans.
4. Light weighting materials, improved blade designs, optimized rake angles, high-speed operations (>400 rpm) are the solutions for the future ceiling fans.
5. Motor vibration caused by magneto strictive effect of ferromagnetic materials

VIII. CONCLUSION
Technological advancements in electric ceiling fan related to its electric motors, power controllers and mechanical designs such as blade designs CFD analysis are reviewed comprehensively. Present energy efficient ceiling fans are explored with their performances. Still, there is a scope to reduce a fan's

power consumption by at least 20% based on the innovations made in motors, controllers, and mechanical designs as highlighted in future technologies.

ACKNOWLEDGMENT

The authors would like to thank Stone Link Design Labs, Chennai, for procuring the fans; the School of Electrical Engineering, VIT University, Chennai, India; and the Department of Energy Technology, Aalborg University, Esbjerg, Denmark.

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