DESIGN AND DEVELOPMENT OF ENERGY EFFICIENT SINGLE PHASE INDUCTION MOTOR FOR FAN APPLICATIONS

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DESIGN AND DEVELOPMENT OF ENERGY EFFICIENT SINGLE PHASE INDUCTION MOTOR FOR FAN APPLICATIONS

by

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CERTIFICATE

This is to certify that the thesis entitled, **"Design and Development of Energy Efficient Single Phase Induction Motor for Fan Applications"** being submitted by **Mr. Utkarsh Sharma** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Utkarsh Sharma has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

Date:

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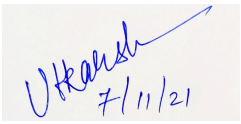

Utkarsh Sharma

ABSTRACT

Ventilating fans, particularly ceiling fans are the utmost need during summers and hot climatic conditions in India and other countries near equator. The majority of ceiling fans and exhaust fans employ permanent capacitor single phase induction motors (SPIMs). The operational number of ceiling fans and exhaust fans is enormous in countries like India, Brazil, China, USA and many more. Ceiling fans have been overlooked for efficiency throughout because of low power consumption (70 W-100 W). However, with the rising population, number of ceiling fans and exhaust fans have become exponentially high, hence their power consumption has also become enormous.

This research work deals with the analysis, design, development and testing of energy-efficient ceiling fans and exhaust fans. The radial flux SPIM based ceiling fans have a unconventional pancake type structure with two phase windings in an inner stator in very small diameter. Unlike conventional SPIMs, there are three magnetic paths of flux in the stator, each of which has to operate without saturation for minimal input power consumption. In this work, it is found that the analytical solution of the performance of the ceiling fan SPIMs is inaccurate, hence, transient mechanical finite element analysis (FEA) based solution is proposed for the performance analysis and design improvement process. The same is validated on 45 W and 50 W commercial ceiling fan motors through experimental results. The mechanical characteristics of the fan blades are identified using a torque measurement setup. A static shaft-shaft torque transducer is used for measurement of the restraining torque. Hence, the torque versus speed characteristics of the blades are identified using the curve fitting method. In this work, a simple method is proposed, which uses no load and block rotor tests along with virtual tests (from FEA) on the baseline design for identification of satisfactory performance of the ceiling fan motor for quality check of large number of motors at production level. Vari-

ous speed controllers are commercially available for controlling the speed of the ceiling fans. In this work, their impact on the performance of ceiling fan motors and power consumption is looked upon. The influence on the electrical performance and the speed control are validated with experimental tests, while the electrical performance as well as electromagnetic torque developed is analyzed using the co-simulation with FEA. The most energy-efficient ceiling fan SPIM presently consumes as low as 45 W for standard air delivery of 210 cubic meter per minute (CMM). The design of ceiling fan for 16 pole motor has been improved using the statistical methods based FEA simulations. Taguchi's orthogonal arrays are used to discretely improve the performance of the motor. A 16 pole motor design is improved to provide a service value (ratio of the air delivery in CMM and input power consumed) greater than "6". The improved design is developed, prototyped and tested for satisfactory performance for five star rating as per IS 374 and BEE five star ratings. A 14 pole configuration for radial flux ceiling fan SPIM is analyzed for improvement in the performance of motor. The design improvement along with reduction in the overall cost of the motor by using aluminium windings is proposed. Axial flux topology is explored for the use in ceiling fan motor because of higher conductor area as compared to the radial flux topologies. An analytical closed form solution is developed for the optimal design of the axial flux SPIM (AFPIM). The optimal design is verified using the transient FEA. The exhaust fan motors are the significantly higher power motors, as compared to ceiling fan motors, which are used in domestic as well as industrial environments for continuous duty. The design of a commercial exhaust fan motor is improved using a GA based computer aided design program. The optimal design results are verified using transient FEA. The exhaust fan is a type of unsymmetrical two phase machine with permanent capacitor. The transient analysis of the exhaust motor is dealt with using phase variable model and d-q axis theory. The simulated results are verified using the experimental

results on the commercial exhaust fan motor.

सार

वेंटिलेटिंग पंखे, विशेष रूप से सीलिंग फैन की अत्यधिक आवश्यकता भारत और भूमध्य रेखा के निकट देशों में गर्मियों और गर्म जलवायु परिस्थितियों के दौरान होती है। ज्यादातर सीलिंग फैन और एग्जॉस्ट फैन में सिंगल फेज इंडक्शन मोटर्स (एसपीआईएम) लगाते हैं। सीलिंग फैन और एग्जॉस्ट फैन की परिचालन संख्या भारत, ब्राजील, चीन, अमेरिका और कई देशों में बहुत अधिक है। कम बिजली खपत (70 वाट–100 वाट) के कारण सीलिंग फैन की दक्षता की अनदेखी हमेशा से की जाती रही है। हालांकि, बढ़ती आबादी और सीलिंग फैन की संख्या के साथ, सीलिंग फैन और एग्जॉस्ट फैन की दक्षता में सुधार के लिए ध्यान दिया जा ना चाहिए।

इस शोध कार्य में एनर्जी एफिशन्ट सीलिंग फैन और एग्जॉस्ट फैन के विश्लेषण, डिजाइन, विकास और टेस्टिंग का कार्य किया गया है। रेडियल फ्लक्स (एसपीआईएम) आधारित सीलिंग पंखे की गैर-पारंपरिक पैनकेक संरचना में बहुत् छोटे व्यास की दो फेज की वाइंडिंग स्टेटर में होती है। पारंपरिक (एसपीआईएम) के समान स्टेटर में फ्लक्स के तीन चुंबकीय पथ होते हैं, जो कि सेचुरेटेशन बिना न्यूनतम इनपुट बिजली खपत के लिए संचालित होते हैं। यह पाया गया है कि सीलिंग फैन (एसपीआईएम) की परफ़ोमेन्स के लिए एनेलिटिक्ल सोल्युशन सही नहीं है, अतः इस कार्य में परफ़ोमेन्स एनेलीसिस और डिजाइन सुधार प्रक्रिया के लिए ट्रानजिएन्ट मैकेनिकल एफईए आधारित सोल्युशन प्रस्तावित है। इसे प्रायोगिक परिणामों के माध्यम से 45 वाट और 50 वाट वाणिज्यिक सीलिंग फैन मोटर्स पर मान्य किया गया है। पंखे के ब्लेड की यांत्रिक विशेषताओं को एक टॉर्क माप सेट अप का उपयोग करके पहचाना जाता है। एक स्थिर शाफ्ट-शाफ्ट टॉर्क ट्रांसड्यूसर का उपयोग निरोधक टॉर्क के मापन के लिए किया जाता है। इसलिए ब्लेड की टॉर्क बनाम गति विशेषताओं की पहचान वक्र फिटिंग विधि का उपयोग करके की जाती है।

इस कार्य में, एक सरल विधि प्रस्तावित है जो बेसलाइन डिज़ाइन पर नो लोड और ब्लॉक रोटर परीक्षणों का उपयोग वर्चुअल परीक्षणों के साथ-साथ सीलिंग फैन मोटर के संतोषजनक प्रदर्शन की पहचान के लिए उत्पादन स्तर पर बड़ी संख्या में मोटरों की गुणवत्ता जांच के लिए उपयोग करती है। हालांकि, सीलिंग फैन मोटर के प्रदर्शन और बिजली की खपत पर उनके प्रभाव को देखा गया है। विद्युत प्रदर्शन और गति नियंत्रण पर प्रभाव प्रयोगात्मक परीक्षणों के साथ मान्य किया गया है, जबकि विद्युत प्रदर्शन के साथ-साथ विकसित विद्युत चुम्बकीय टॉर्क का विश्लेषण एफईए के साथ सह-सिमुलेशन का उपयोग करके किया गया है।

वर्तमान में सबसे अधिक एनर्जी एफिशन्ट सीलिंग फैन एसपीआईएम 45 वाट जितनी कम खपत 210 क्यूबिक मीटर प्रति मिनट (सीएमएम) के मानक वायु वितरण के लिए उपभोग करता है। 16 पोल मोटर के लिए सीलिंग फैन के डिजाइन का सुधार एफईए सिमुलेशन पर आधारित सांख्यिकीय विधियों का उपयोग करके किया गया है। टागुची ऑर्थोगोनल एरे का उपयोग मोटर के प्रदर्शन को पूरी तरह से सुधार के लिए किया जाता है। 16 पोल मोटर का सुधार "6" से अधिक सेवा मूल्य (हवा की डिलीवरी सीएमएम में और इनपुट बिजली की खपत का अनुपात) प्रदान करने के लिए किया गया है।

आईएस 374 और बीईई की पांच सितारा रेटिंग के अनुसार उन्नत डिजाइन, प्रोटोटाइप और संतोषजनक प्रदर्शन परीक्षण पांच सितारा रेटिंग के लिए विकसित किया गया है। एक 14 पोल कॉन्फ़िगरेशन रेडियल फ्लक्स सीलिंग फैन एसपीआईएम का विश्लेषण

मोटर के प्रदर्शन में सुधार के लिए किया गया है। एल्यूमीनियम वाइंडिंग का उपयोग करके मोटर की समग्र लागत में कमी के साथ-साथ डिजाइन में सुधार प्रस्तावित है। उच्च कंडक्टर क्षेत्र की वजह से एक्सियल फ्लक्स टोपोलॉजी को रेडियल फ्लक्स टोपोलॉजी की तुलना में सीलिंग फैन मोटर में उपयोग के लिए पता लगाया गया है। एक्सियल फ्लक्स एसपीआईएम (एएफपीआईएम) के ऑप्टीमल डिजाइन के लिए एक एनेलिटिक्ल क्लोज्ड फॉर्म सोल्युशन विकसित किया गया है। ऑप्टीमल डिजाइन का सत्यापन ट्रानजिएन्ट एफईए का उपयोग करके किया गया है। एग्जॉस्ट फैन मोटर्स काफी उच्च शक्ति वाली मोटरें हैं जिनका उपयोग घरेलू और औद्योगिक वातावरण में निरंतर ड्यूटी के लिए किया जाता है। एक व्यावसायिक एग्जॉस्ट फैन मोटर्स के डिजाइन में सुधार जीए आधारित कंप्यूटर एडेड डिजाइन प्रोग्राम का उपयोग करके किया गया है। ऑप्टीमल डिजाइन का सत्यापन ट्रानजिएन्ट एफईए का उपयोग करके किया गया है। एग्जॉस्ट फैन एक प्रकार की असममित दो फेस मशीन है जिसमें स्थायी संधारित्र होता है। एग्जॉस्ट मोटर का ट्रानजिएन्ट एनेलीसिस फेस वेरीऐबल मॉडल और डी-क्यू सिद्धांत का उपयोग करके किया गया है। व्यावसायिक एग्जॉस्ट फैन मोटर के सिमुलेटेड परिणामों को प्रयोगात्मक परिणामों से सत्यापित किया गया है।

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LIST OF ABBREVIATIONS

AC	Alternating Current
AFSPIM	Axial Flux Single Phase Induction Motor
BLDC	Brushles Direct Current Motor
CMM	Cubic Meter Per Minute
DC	Direct Current
DoE	Design of Experiments
EMF	Electro-Motive Force
FEA	Finite Element Analysis
FF	Fil Factor
ID	Inner Diameter
MMF	Magneto-Motive Force
OA	Orthogonal Array
OD	Outer Diameter
pf	Power Factor
PM	Permanent Magnet
PMSM	Permenent Magnet Synchronous Motor
RFSPIM	Radial Flux Single Phase Induction Motor
SPIM	Single Phase Induction Motor

LIST OF SYMBOLS

A_b	Rotor Bar Area
A_{Aux}	Auxiliary Winding Slot Area
A_{Main}	MainWinding Slot Area
α_{skew}	Rotor Bar Skewing Angle
$b_{os}1$	Main Winding Slot Opening Width
$b_{os}2$	Auxiliary Winding Slot Opening Width
$B_{g_{av}}$	Average Flux Density
$B_{t,aux}$	Average Flux Density of Auxiliary Winding Teeth
$B_{t,main}$	Average Flux Density of Main Winding Teeth
C	Capacitor in Series with Auxiliary Winding
D	Diameter of the Airgap
D_b	End Ring Mean Diameter
D_{ro}	Outer Diameter of the Rotor
D_{ri}	Inner Diameter of the Rotor
D_{so}	Outer Diameter of the Stator
D_{si}	Inner Diameter of the Stator
G_a	Wire Gauge of Auxiliary Winding
G_m	Wire Gauge of Main Winding
h_e	End Ring Height
i_{as}	Current in stator phase a
i_{bs}	Current in stator phase b
i'_{ar}	Current in rotor phase a referred to stator phase a
i'_{br}	Current in rotor phase b referred to stator phase b
J	Moment of Inertia of Motor
L_{st}	Stack Height of the Motor
l_g	Airgap Length Per Side
λ_{as}	Flux linkage of stator phase a
λ_{bs}	Flux linkage of stator phase b
λ'_{ar}	Flux linkage of rotor phase a referred to stator phase a
λ'_{br}	Flux linkage of rotor phase b referred to stator phase b

L_{ss}	Self inductance of stator phase a
L_{SS}	Self inductance of stator phase b
L'_{rr}	Self inductance of rotor phase a referred to stator phase
L'_{rR}	Self inductance of rotor phase b referred to stator phase
L_{ms}	Magnetizing inductance of stator phase a
L_{mS}	Magnetizing inductance of stator phase b
N_a	Turns in Auxiliary Winding
N_m	Turns in Main Winding
N_r	Rated Speed of the Rotor
N_R	Number of Rotor Bars
P	Number of Poles of Motor
σ_{al}	Conductivity of Aluminium
σ_{Cu}	Conductivity of Copper
T_e	Electromagnetic Torque
v_{as}	Voltage applied to stator phase a
v_{bs}	Voltage applied to stator phase b
v'_{ar}	Voltage applied to rotor phase a referred to stator phase a
v'_{br}	Voltage applied to rotor phase b referred to stator phase b
v_C	Voltage across capacitor
w_e	End Ring Width
$W_{t,aux}$	Width of the Auxiliary Winding Teeth
$W_{t,main}$	Width of the Main Winding Teeth
w_{tr}	Rotor Teeth Width