Analysis of Steady-State and Transient Performance of Two-Phase PM Motors for Computer Fans

J. F. Gieras, *Fellow, IEEE,* D. Chojnowski, P. Mikulski

***Abstract*-- Performance characteristics of small two-phase permanent magnet (PM) brushless motors for computer case cooling fans have been investigated. Performance characteristics obtained from analytical calculations have been compared with the test results. A laboratory test equipment for fast measurements of performance characteristics has been built.**

***Index Terms* -- Brushless motor, permanent magnet, fan, single phase, analysis, steady-state performance, transient characteristics, industrial tests.**

I. Introduction

Small two-phase permanent magnet (PM) brushless motors for computer and other electronics equipment cooling fans are ones of the most popular electric motors. The central processing unit (CPU) generates the most heat in a typical personal computer (PC). This heat needs to be removed quietly and efficiently. It is estimated that there are more than 2 billion PCs in the use in 2015. So that the number of fan motors nowadays well exceeds 2 billion. In spite of large number of single-phase PC brushless motors installed in computers, very few research papers have been devoted to these motors [1-4].

Computer cooling fans are typically based on two-phase brushless DC (BLDC) motors with inner stator and outer PM rotor drawing between 1 and 50 W of electric power.

An integrated circuit (IC) on the printed circuit board (PCB) controls the stator windings, energizes the coils, and changes the magnetic field that interact with PMs located in the outer rotor to keep the motor spinning. Many PC motherboards feature hardware and software that regulates the speed of fans based on the processor and computer case temperatures.

Solutions have been proposed to provide variable speed control for two-phase brushless motor assemblies, while limiting the number of wires connecting to such assemblies to three, a desirable cost saving objective [5,6].

The speed control of two-phase brushless motor assemblies can be done by adjusting the DC voltage to the motor, applied between the supply and ground wires [6]. The third wire is then used for the tachometer's feedback signal. A control IC includes a speed monitor, which receives a tachometer signal from the fan.

Control signals generated by the system PCB and provided to the fan assembly can use the same wire as tachometer signals generated in the fan assembly [6].

From the user point of view, there are PC fan motors with a two-pin, three-pin and four-pin connector. Looking from the key-side of the connector, the number 1 is the negative power supply, 2 is the positive power supply, 3 is the tachometer and 4 is the PWM control.

From the standpoints of acoustic noise, reliability, and power efficiency, the most preferable method of fan control is the use of high-frequency (>20 kHz) pulse width modulation (PWM) drive.

The latest technology (Yen Sun Technology) in computer cooling fans is the tip-driven fan that moves the motor out of the hub of the fan, and puts it around the edge [8]. The impeller blades are surrounded by a ring studded with 12 magnets, which are acted upon by four coils that're located at the corners of the housing of the fan. The tips of the blades can also be made of a hard magnetic material and magnetized in radial direction [9].

II. Construction of PM BLDC Fan Motors

The cost effective two-phase brushless motors for computer fans have a salient pole inner stator and ring-shaped outer PM rotor. The outer PM rotor is integrated with the fan blades facilitating air flow [1 – 4]. The housing is mechanically connected with the inner stator of the motor with the aid of a spider structure (Fig. 1). The details of construction of a PC fan motor are shown in Fig 2.

A Hall sensor detects the polarity of PMs and via solid state devices switches the DC voltage from one stator coil to another. The speed of the fan motor is controlled by adjusting either the DC voltage or pulse width in low-frequency PWM [10].

In spite the PM BLDC motor has four dead spots per revolution, it has god self-starting capability. Since the rotor rests between the poles of PMs at zero-current state

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(Fig. 3), and instantly rotates 45° when first switched on, it will not stop on one of its dead spot.

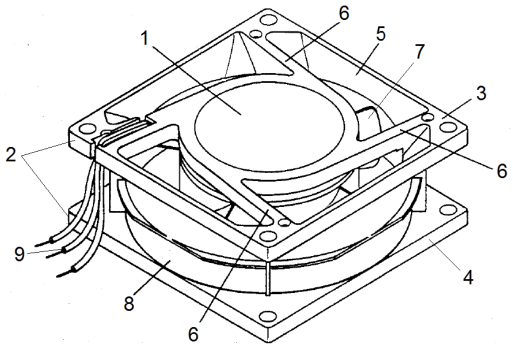

Fig. 1. PC fan: 1 – PM BLDC motor, 2 – housing, 3 – front surface, 4 – rear surface, 5 – Venturi set up, 6 – struts of a spider structure, 7 – blades, 8 – cylindrical exterior of the housing, 9 – leads [5].

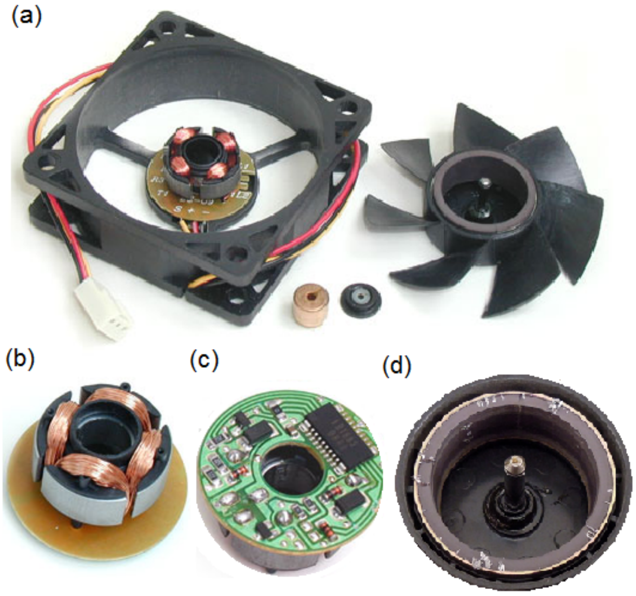

Fig. 2. Construction of a PM BLDC motor drive for computer fans: (a) disassembled motor; (b) inner stator with four salient poles; (c) PCB; (d) external rotor with 4-pole PM rotor.

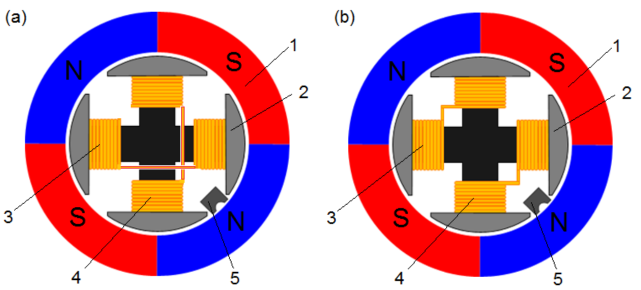

Fig. 3. Stator coils, PM polarity and Hall sensor position: (a) opposite coils connected in pairs; (b) neighboring coils connected in pairs. 1 – PM, 2 – stator pole, 3 – coil of one phase, 4 – coil of the second phase, 5 – Hall sensor located between two stator poles.

A. *Stator and PM rotor*

Two phase stator winding consists of four coils wrapped around the stator pole cores. There are four coils in the inner stator (Fig. 3b), while two neighboring coils have different magnetic polarity. The coils are connected in pairs, either each one with its opposite coils (Fig. 3a), or with its neighboring coils (Fig. 3b). Around the perimeter of the outer rotor, there are four PMs in N-S-N-S pattern (Fig 2b, Fig. 3).

Typically, a 12-V DC cooling fan motor consists of a rotor-blade assembly containing a 4-pole PM, and a 4-pole stator. A Hall sensor detects the rotating magnetic field and switches 12 V DC from one stator coil set to another (Fig. 3). Varying the supplied DC voltage can vary the speed of most fans. A 12-V DC fan might start rotating with 3.5…5.0 V DC voltage applied, and increase its speed when increasing voltage is supplied.

B. *Electronic Circuit*

Typical electronic circuits for feeding and controlling PC fan motors are shown in Fig. 4. The common cooling fans used in computers use standardized connectors with two to four pins. The first two pins are always used to deliver power to the fan motor, while the rest can be optional, depending on fan design and type:

- ground;
- power (+12 V);
- sense: provides a tachometer signal that measures the actual speed of the fan as a pulse train, frequency being proportional to speed (with each fan rotation, there are two pulses sent through this pin;
- control: provides a PWM signal, which gives the ability to adjust the rotation speed without changing the input voltage delivered to the cooling fan.

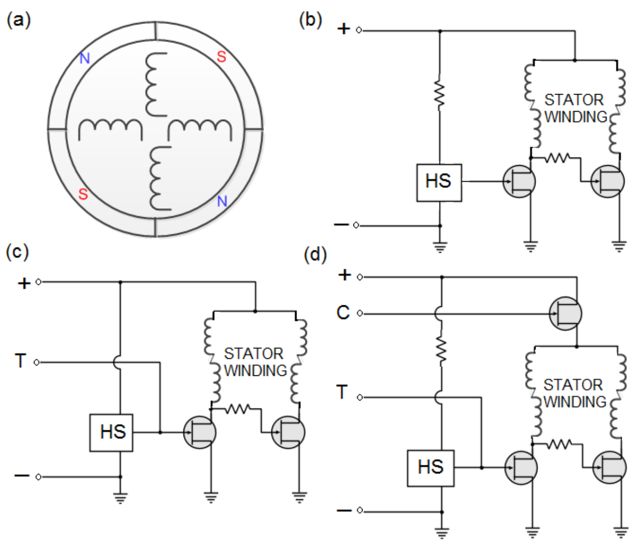

Fig. 4. Simplified diagrams of built-in electronic circuit (PCB): (a) stator coils and outer PM rotor; (b) circuit with two-pin connector (no provision to control the fan by an external signal); (b) circuit with three-pin connector; (d) circuit with four-pin connector [10]. The “+” and “-“are power supply terminals, C is the control pin, T is the tachometer pin (speed sensing) and HS is the Hall sensor.

The PWM is a common method of controlling computer fans. A PWM-capable fan is usually connected to a 4-pin connector (Fig. 4d). The sense (tachometer) pin is used to relay the rotation speed of the fan. The control pin is an open-drain or open-collector output, which requires a pull-up to 5.0 V or 3.3 V in the fan. Unlike linear voltage regulation, where the fan voltage is proportional to the speed, the fan is driven with a constant supply voltage; the speed control is performed by the fan based on the control signal.

The control signal is a square wave operating at 25 kHz, with the duty cycle determining the fan speed. Typically, a fan can be driven between about 30% and 100% of the rated fan speed, using a signal with up to 100% duty cycle. The exact speed behavior (linear, off until a threshold value, or a minimum speed until a threshold) at low control levels is manufacturer dependent [7].

Speed regulators are used by many manufacturers to keep the fans quieter. Control is performed on a temperature basis. Measurement sensors constantly monitor temperatures (such as on cooling elements). If the temperature is too high, then the control unit increases the operating voltage for the fan and hence the rotor speed and air flow.

C. Bearings

Bearings are a critical component in a cooling fan because bearings make the fan rotate smoothly. Bearings reduce friction, allow the fan to operate at high speeds, and are partly responsible for the life expectancy of a cooling fan in a computer and the noise level of fans. Three types of bearings can be used in a cooling fan: (a) sleeve bearings, (b) ball bearings, and(c) fluid dynamic bearings.

D. Specifications of Investigated Motor

The specifications of the investigated two-phase PM brushless motor are given in Table 1. The disassembled motor is shown in Fig. 5. The stator housing and fan blades have been removed.

TABLE I

Specifications of investigated computer case fan motor

Rated input power	1.10 W
No-load speed	1500 rpm
Rated voltage	12 V DC
Rated current	0.091 A
Number of poles	4
Stator core outer diameter	29.4 mm
Axial length of stator stack	5 mm
PM Outer diameter (OD)	35 mm
PM inner diameter (ID)	31.6 mm
Axial length of PM	9.2 mm

The ring-shaped PM is made of anisotropic barium ferrite with remanent magnetic flux density B_r = 0.4 T and coercivity H_c = 260 kA/m. The built-in PWM solid state converter receives position information from Hall sensors placed in the q-axis of the stator (Fig. 3).

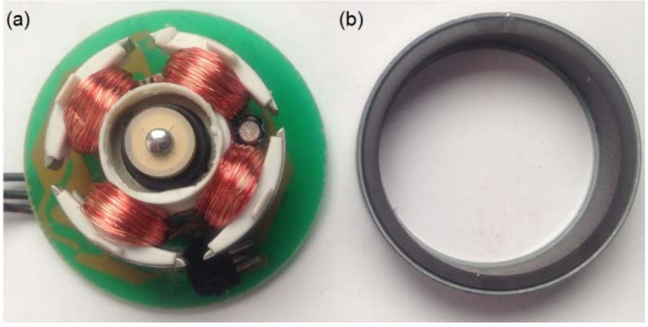

Fig. 5. Investigated PM BLDC motor for PC fan: (a) inner stator with PCB; (b) ring-shaped PM.

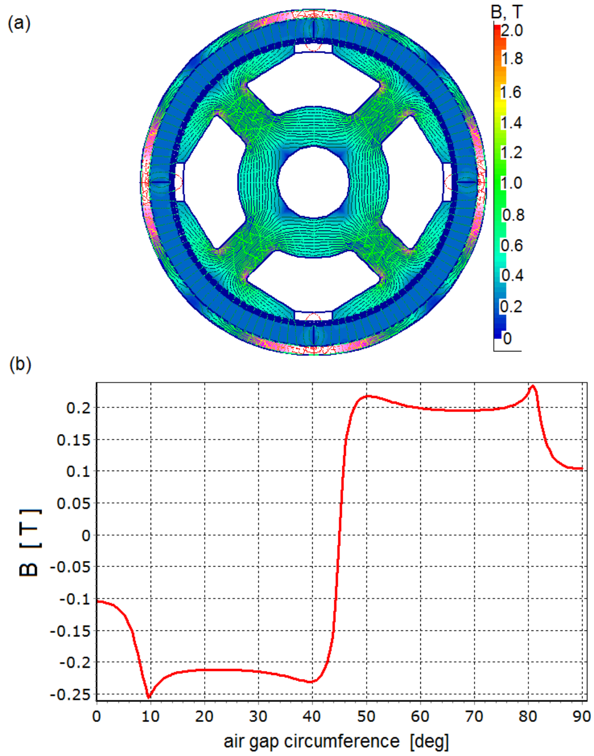

Fig. 6. Magnetic field distribution in the investigated two-phase fan PM BLDC motor as obtained from the 2D FEM analysis: (a) flux lines at nominal load; (b) radial component of the air gap magnetic flux density at no-load.

The cross section of the motor and magnetic flux distribution is shown in Fig. 6a. The radial component of the magnetic flux density distribution in the air gap is plotted in Fig. 6b.

The speed is controlled by the PWM signal. In the event that the PWM [1] signal is 0%, the motor will continue rotating at the minimum speed, which is about 500 rpm.

The motor can start up at 3.5 V and work in a voltage range of 3.5 to 14 V. The peak power consumption is 1.1

[1] PWM is a modulation of the duty cycle. The duty cycle reflects the switch between two fixed values, such as 0 V and 5V. The frequency of the signal never changes in the process. The only factor that varies is the rhythm of "on time" and "off time". For example: a 50% PWM would set a fan – such a CPU or casing fan – running at approximately half of its maximum speed

W. The motor is equipped with fluid dynamic bearings with a service life of 300,000 hours. Even at maximum speed, the fans offer a very quiet operation below 19.2dB(A).

III. Experimental Tests

Figs 7, 8 and 9 show the results of steady-state laboratory measurements, while Fig 10 shows the current and voltage curves versus time at starting, Fig 11 shows switching on the voltage and current at locked rotor, and Fig. 12 shows the switching off the voltage at no load. The maximum load torque (Fig. 8b) for the investigated motor is 0.36 Ncm.

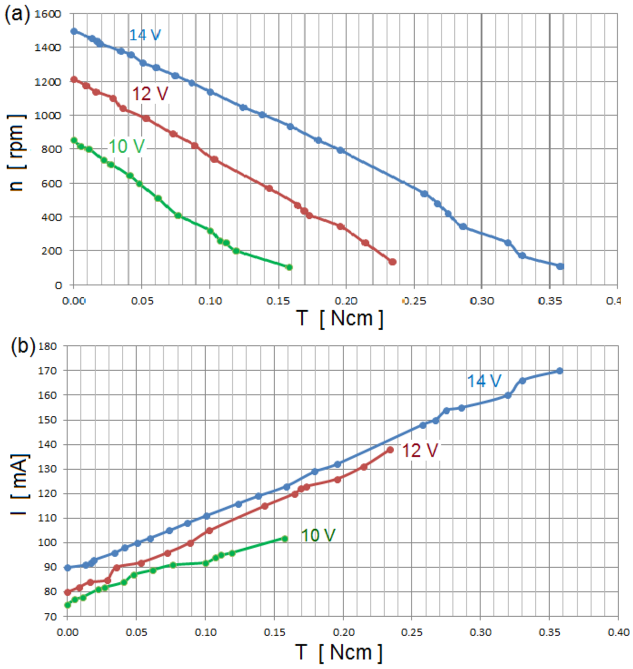

Fig. 7. Steady-state test results: (a) speed versus torque; (b) input current versus torque.

The steady-state characteristics (Figs 7 to 9) have been measured for three levels of the controller input voltages, i.e., 14, 12 and 10 V DC. The input voltage slightly drops as the load torque increases (Table II).

TABLE II
Reduction of voltage with the load (Fig. 7a, 8b)

DC voltage, V	14.0	13.6	13.2
Load torque, Ncm	0	0.15	0.32
DC voltage, V	12.0	11.4	10.5
Load torque, Ncm	0	0.10	0.22
DC voltage, V	10.0	9.26	8.55
Load torque, Ncm	0	0.07	0.15

The increase in the current (slope angle) with the load torque is similar for all voltages, i.e., 14, 12 and 10 V DC (Fig 7b).

The peak shaft power is 0.16 W for 14 V, 0.086 W for 12 V and 0.035 W for 10 V.

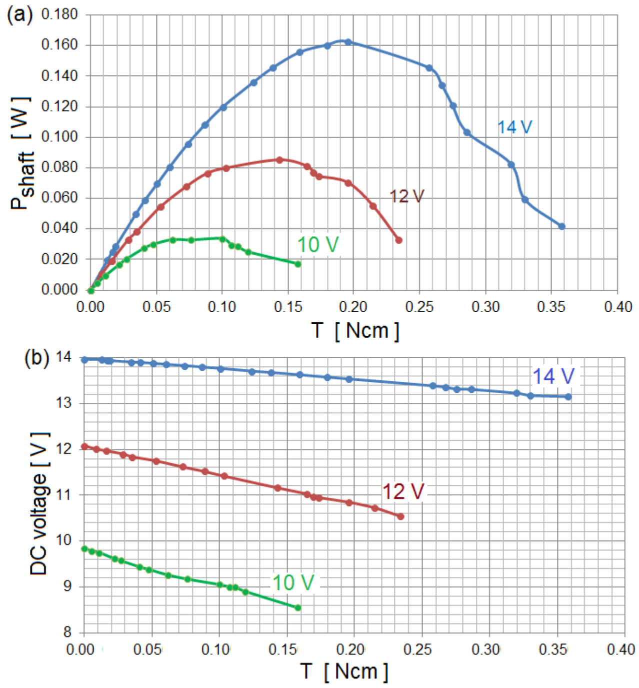

Fig. 8. Steady-state test results: (a) shaft power versus torque; (b) DC voltage drop with load.

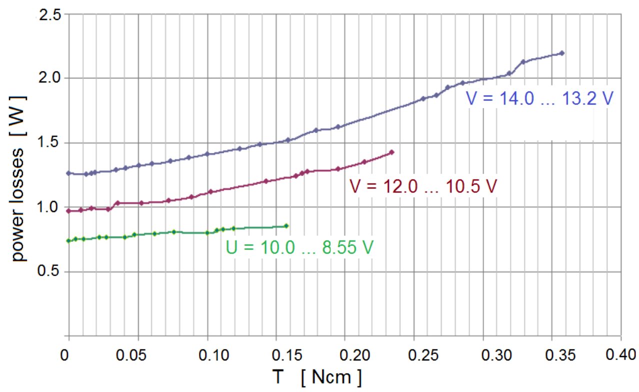

Fig. 9. Power losses versus load torque at constant DC voltage.

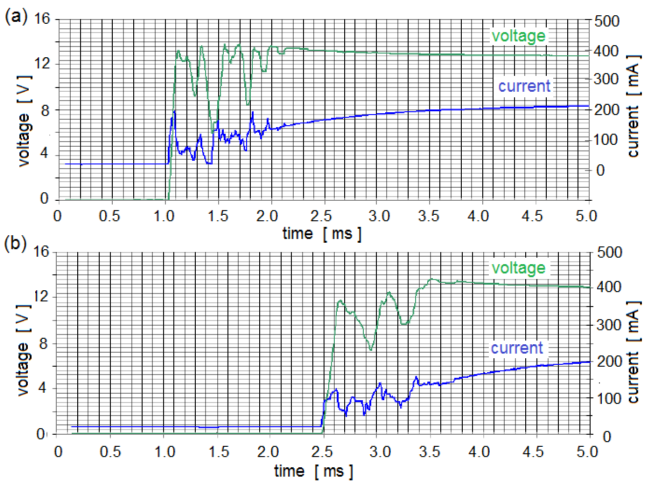

Fig. 10. Voltage and current waveforms at starting: (a) at no-load; (b) under maximum load of 0.36 Ncm. Test results.

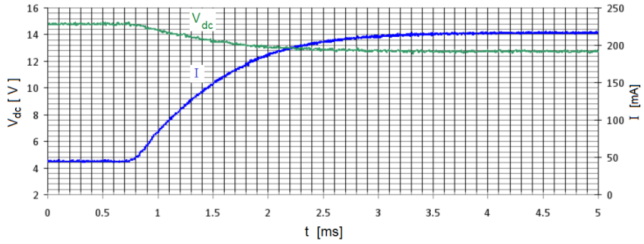

Fig. 11. Switching on the voltage at locked rotor. Voltage and current curves versus time.

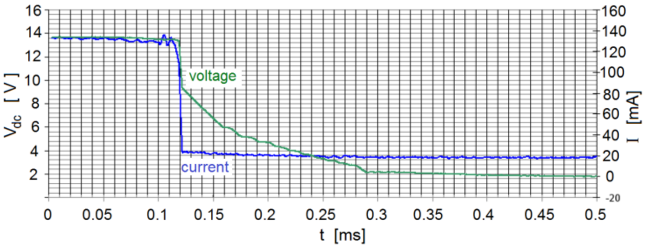

Fig. 12. Switching off the voltage at no load. Voltage and current curves versus time.

At starting, the steady-state voltage and current is achieved after about 3.5 ms at no load (Fig. 109a) and after 2.5 ms at maximum load 0.36 Ncm (Fig. 10b).

The total power losses in the motor and solid state controller are high (Fig. 9) and exceed more than 10 times the maximum output power (Fig. 8a).

IV. Comparison of Calculations with Test Results

Figs 12 and 13 show the comparison of calculated performance characteristics with the test results. All calculations of characteristics have been done using analytical approach. The efficiency includes both the motor and solid state controller losses. As expected, for this type and size of PM BLDC motors, the efficiency is very low and does not exceed 10% at 14 V, 6.5% at 12 V and 4% at 10 V (see also Fig. 9).

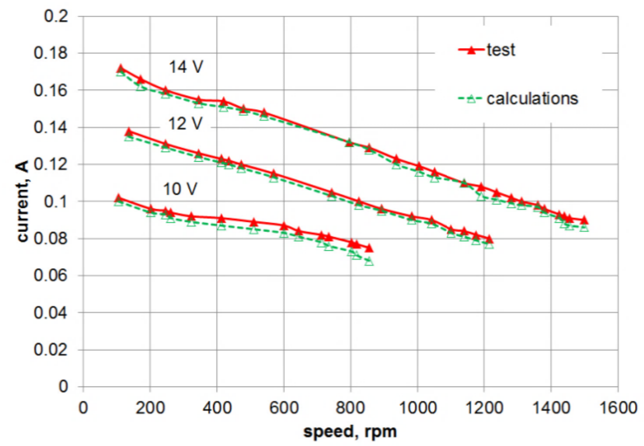

Fig. 13. Load curves: stator AC current versus speed at constant DC voltage.

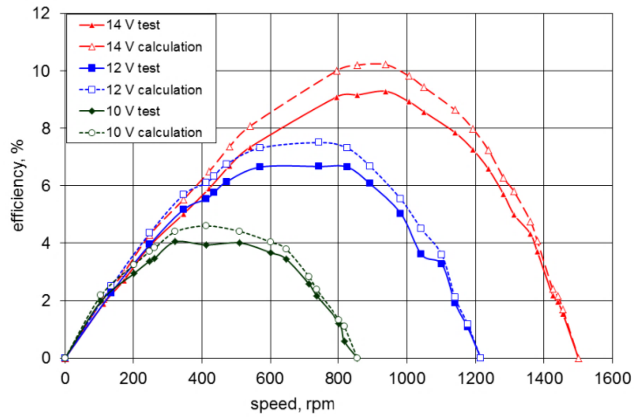

Fig. 14. Load curves: efficiency versus speed at constant DC voltage.

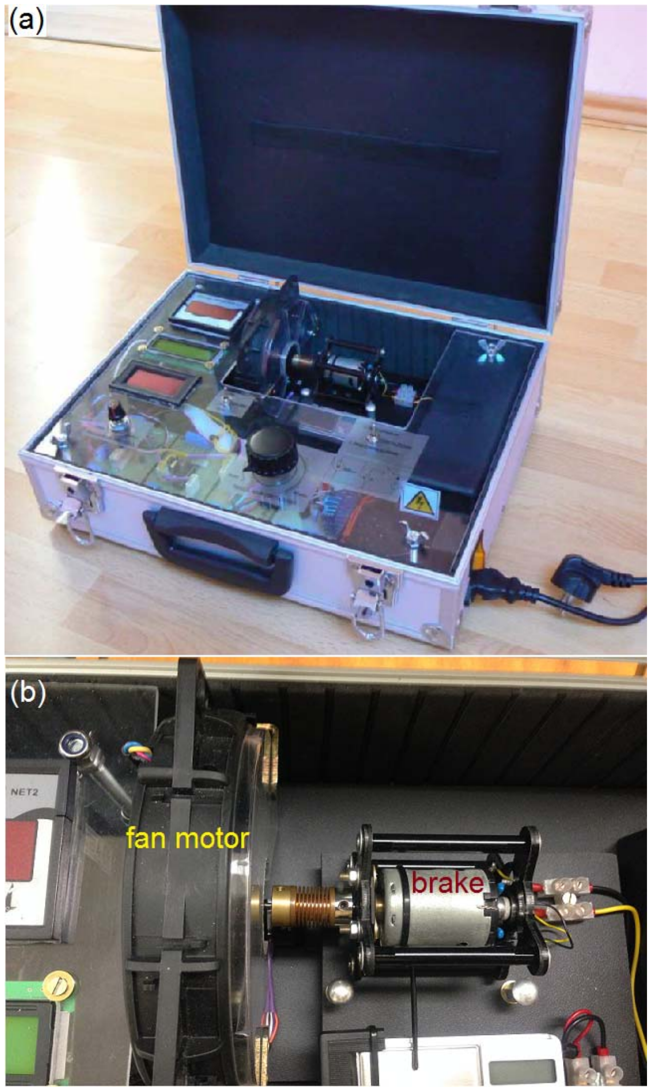

Fig. 15. A portable equipment for industrial tests: (a) general view; (b) tested fan motor and electromagnetic brake.

V. Portable Laboratory Equipment

A portable equipment for fast measurements of steady-state and dynamic performance of two-phase PM BLDC motors for computer fans has been built as a part of this research (Figs 15, 16 and 17). This equipment allows for detection of faulty motors and selection of the best motors in computer assembly plants.

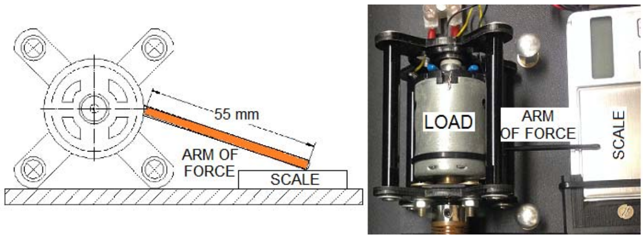

Fig. 16. Method of measurement of torque of investigated motor.

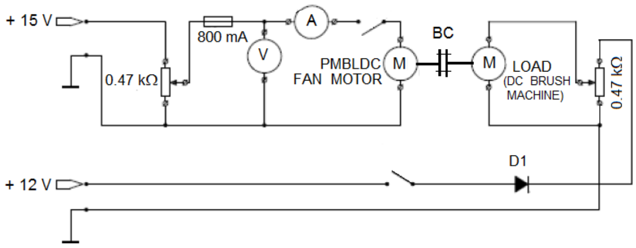

Fig. 17. Power circuit of investigated motor.

As a load (brake), a 2.5-W, 12 V DC brush motor equipped with external bearing has been used. The load torque has been measured with the aid of a precision digital scale (Fig. 16).

The rotational speed has been measured using a timer that operates as a counter. The timer receives pulses generated by an optical sensor and a mirror disk being placed on the rotor of the investigated motor. The counted pulses have been red in 1-s intervals.

VI. Conclusions

Although a two-phase fan PM BLDC motor with outer rotor is one of the most popular motors, a few research papers on analysis and performance characteristics of these motors have been published so far. The authors believe that the presented paper is the first paper, which contain extended laboratory tests and their comparison with analytical prediction. In this paper:

(a) the magnetic circuit of the motor has been analyzed using the 2D FEM;

(b) full laboratory steady-state and transient tests have been performed;

(c) experimental test results have been compared with analytical calculations – good agreement has been obtained;

(d) a portable equipment for fast measurements of steady-state and dynamic performance of two-phase PM BLDC motor for computer fans has been designed and built.

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VIII. Biography

Jacek F. Gieras (M'83–SM'87–F'02) graduated in 1971 from the Technical University of Lodz, Poland, with distinction. He received his PhD degree in Electrical Engineering (Electrical Machines) in 1975 and Dr habil. degree (corresponding to DSc), also in Electrical Engineering, in 1980 from the University of Technology, Poznan, Poland. His research area is Electrical Machines, Drives, Electromagnetics, Power Systems, and Railway Engineering. From 1971 to 1998 he pursued his academic career at several Universities worldwide including Poland (Technical University of Poznan and Academy of Technology and Agriculture Bydgoszcz), Canada (Queen's University, Kingston, Ontario), Jordan (Jordan University of Sciences and Technology, Irbid) and South Africa (University of Cape Town). He was also a Central Japan Railway Company Visiting Professor at the University of Tokyo (Endowed Chair in Transportation Systems Engineering), Guest Professor at Chungbuk National University, Cheongju, South Korea, and Guest Professor at University of Rome *La Sapienza*, Italy. In 1987 he was promoted to the rank of Professor (life title given by the President of the Republic of Poland). Since 1998 he has been affiliated with United Technologies Corporation, U.S.A.. In 2007 he also became Faculty Member (Full Professor) of the University of Technology and Life Sciences in Bydgoszcz, Poland. He authored and co-authored 11 books, over 250 scientific and technical papers and holds over 70 patents and patent publications. The most important books are Linear Induction Motors, Oxford University Press, 1994, U.K., Permanent Magnet Motors Technology: Design and Applications, Marcel Dekker Inc., New York, 1996, 2nd edition 2002, 3rd edition 2010 (Taylor & Francis), Linear Synchronous Motors: Transportation and Automation Systems, CRC Press LLC, Boca Raton, Florida, 1999, 2nd edition 2011, Axial Flux Permanent Magnet Brushless Machines, Springer-Kluwer Academic Publishers, Boston-Dordrecht-London, 2004, 2nd edition 2008, Noise of Polyphase Electric Motors, CRC Press - Taylor & Francis, 2005, and Advancements in Electric Machines, Springer, Dordrecht-London-New York, 2008.

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