A Novel Wind Energy System

Tze-Fun Chan, *Member, IEEE*, and Loi Lei Lai, *Fellow, IEEE*

***Abstract*— A novel wind energy system is proposed and studied in this paper. An axial-flux permanent-magnet synchronous generator (AFPMSG) is directly coupled to a vertical-axis wind turbine (VAWT), which can be an H-Darrieus, Savonius, Hunt turbine, or others. The AFPMSG has an outer-rotor construction for convenient mounting to the turbine rotor structure. The coreless armature winding design eliminates cogging torque and unbalanced magnetic pull, giving smooth operation with low losses. Performance of a prototype generator is studied. The magnetic field distribution of the AFPMSG is studied using a two-dimensional finite element method (FEM) and analytical methods. By using the concept of image magnetic charges, we show that the normal component of flux density is reduced appreciably at the inner and outer circumferential regions.**

***Index Terms*—Axial-flux machine, permanent-magnet synchronous generator, wind energy system, field computation.**

I. INTRODUCTION

POWER generation utilizing wind energy has received greater attention in countries all over the world [1] due to rapid depletion of fossil energy resources. In remote areas, small-scale autonomous wind energy power generation systems reduce grid-connection costs and avoid the transmission losses. In developed regions, distributed wind power systems are also beneficial from environmental and power system reliability considerations. The market potential of wind-energy generators is large because of the surging power demands in developing countries and regions.

In large wind power systems, horizontal-axis wind turbines (HAWTs) are commonly used to drive high-speed induction generators through mechanical gears. Vertical-axis wind turbines (VAWTs), on the other hand, are more suitable for small-scale, distributed wind generation in the urban environment, where space and amenity are two major limiting factors in wind turbine installations. Types of VAWTs include the Darrieus turbine, H-Darrieus turbine, Savonius turbine and , more recently, the Hunt turbine [2]. One advantage of VAWTs compared with HAWTs is that they need not be oriented towards the wind direction without using yawing mechanisms. By exploiting the roof-top space of high-rise buildings, the structural requirement of the VAWT can be greatly reduced for a given energy capture. It has been reported, for example, that around 20% of the power demand of a very tall building can be provided by VAWTs [2]. Roof-top generation using VAWTs will likely become an important form of renewable power generation in urban regions.

VAWTs for use in urban regions are close to domestic premises, hence quiet operation is an important system requirement. By using a direct-coupled wind turbine generator system, the mechanical gear transmission (which is a bulky and expensive device and also a source of audible noise) is eliminated, thereby improving the reliability and reducing the maintenance cost.

A direct-coupled generator has to operate at low speeds (typically from 200 r/min to 600 r/min), hence the pole number of the generator has to be large. A 60 Hz generator running at 300 r/min, for example, must be wound with 24 poles. The axial-flux permanent-magnet synchronous generator (AFPMSG), by virtue of its inherently large diameter-to-axial-length ratio and ability to produce electric energy at low speeds, is a suitable candidate for such an application.

This paper is organized as follows. Section II reviews the PMSG technologies for direct-coupled wind turbines. Section III presents the proposed AFPMSG topology for direct-coupled vertical-axis wind turbines (VAWTs). Section IV gives the computed and experimental performance of the prototype AFPMSG. Section V outlines various methods for computing the magnetic fields in the prototype generator and a conclusion is given in Section VI.

II. PMSGS FOR DIRECT-COUPLED WIND TURBINES

Many PM machine topologies have been proposed for direct-driven wind generator applications [3-14]. According to the direction of magnetic flux, these machines can either be radial-flux type [4,5,8,12] or axial-flux type [3,6,7,9,10,14]. For each type of machine, various electromagnetic designs are also possible, e.g. the outer-rotor design [5], modular design [7,8], the TORUS design [3,6,9], coreless generator [12,14], and concentrated winding design [12], etc.

Spooner and Williamson [4] developed a radial-flux, inner-rotor permanent magnet generator for direct drive wind turbines. Fractional slot winding was used for the prototype generator. Experimental waveforms were given for the experimental generator (26-pole, single-layer winding in 30 slots). The no-load e.m.f. was fairly sinusoidal but the coil e.m.f. had marked harmonic distortion.

Tze-Fun Chan is with the Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, P.R. of China (e-mail: eetfchan@polyu.edu.hk).

Loi Lei Lai is with the Energy Systems Group, School of Engineering and Mathematical Sciences, City University London, Northampton Square, London EC1V 0HB, UK (e-mail: L.L.Lai@city.ac.uk).

Chen et al. [5] studied a 48-pole radial-flux PM generator with outer rotor which enabled the machine to be easily coupled to the wind turbine blades. A magnetic circuit approach was used for design study and verified by finite element analysis. The coil pitch was equal to the slot pitch so that the end winding was shorter and the corresponding copper loss was reduced. The machine was rated at 20 kW, and had an efficiency of 86% at a speed of 170 r/min.

A modular PM generator with axial flux direction was proposed for a direct-drive wind turbine generator by Muljadi et al. [7]. Flexibility of design was achieved since each generator could be expanded to several modules. Each unit module in turn was built from simple modular poles. The stator winding was formed like a torus, linked by flux-focusing guides. The prototype built could deliver a power of 650 W at an efficiency of 75% when driven at 667 r/min. Chen et al. [8] also employed the modular concept but a radial-flux configuration was used. Capacitors were employed for voltage compensation.

B.J. Chalmers et al. [3,6,9] developed an axial-flux permanent-magnet generator called 'torus' for a gearless wind energy system. The stator armature consisted of a laminated toroidal core on which the air gap winding was wound, as in the classical Gramme-ring winding. The cogging torque was therefore eliminated by the slotless design, while the double-sided permanent-magnet rotor minimizes the magnetic pull between the stator and rotor. The experimental machine in [6] had a rating of 5-kW at 200 r/min. Output voltage was practically sinusoidal and an efficiency of 82% could be accomplished at full load. When the air gap lengths on the two sides of the torus are not the same, the resultant magnet pull in the axial direction could be appreciable.

Hwang et al. [10] and Parvianen et al. [13] adopted the more conventional axial-flux machine configuration with toothed iron core. Hwang's machine [10] employed the doubled-sided configuration in which the rotor permanent magnet disk was sandwiched between two toothed stator armature cores. The 24-pole machine was rated at 10 kVA and 380 V when operating at 300 r/min. Parvianen et al. [13] on the other hand developed a single-sided axial machine configuration with open slots. Various combinations of armature slot number and pole number were studied with a view of reducing the cogging torque. A 1.6 kW prototype machine was constructed and was installed in a pilot power plant. Since a single-sided configuration was used, thrust bearings had to be used to withstand the strong magnetic pull between the stator and rotor.

Spooner et al. [12] proposed an ironless, radial-flux, permanent-magnet direct coupled wind generator machine that employed lightweight spoked structures for both rotor and stator. A working flux density of about 0.25 T was produced at the winding. The generator could have a mass typically 20-30% of equivalent designs based on iron-cored magnetic circuits, and the efficiency was greater than 90%. The experimental machine had a specification of 11.1 kW at 150 r/min.

Bumby et al. [14] also developed a double-sided, axial-flux permanent-magnet air-cored generator for small-scale, wind turbines. The features of the prototype included the use of cylindrical NdFeB magnets as well as circular coils wound on bobbins. At 300 r/min the generator is capable of delivering a power of 1 kW with an electrical efficiency exceeding 90%.

In summary, various designs of permanent-magnet generators could be adopted for direct coupled wind turbine applications. The choice of a particular design depends upon expertise of individual research teams and the availability of components and materials, e.g. NdFeB magnets and the technology accessible.

III. Prototype AFPMSG for HAWT

After considering various machine design and manufacturing issues, an outer-rotor, single-sided, axial-flux permanent-magnet synchronous generator configuration was chosen for use in a direct-coupled VAWT system. Compared with an inner-rotor configuration, the outer-rotor AFPMSG provides more saving in core material and mechanical coupling to the turbine rotor is easier. The single-sided permanent-magnet arrangement simplifies the construction without causing unbalanced magnetic pull between the stator and the rotor. Fig. 1 shows the cross-sectional view of a prototype outer-rotor AFPMSG developed for direct-coupled HAWT applications [15]. The machine has 16 poles and a three-phase, full-pitched, double-layer, armature winding. As shown in Fig. 1, the sector-shaped permanent magnets are mounted on the inner surface of one rotor yoke (or back-plate). The disk-shaped, stator armature winding is sandwiched between the magnets and a second rotor yoke. Each armature coil is approximately trapezoidal in shape, with active coil sides running in radial directions. A coreless, double-layer armature winding design is adopted, the conductors being encapsulated in epoxy-resin for mechanical strength. Because of the large number of poles, the armature winding is wound with one coil per pole per phase only. With this 'slotless' design, the conductors in a coil side are spread in the circumferential direction, which is effective in suppressing the space harmonics. Due to the inherently large diameter-to-axial-length ratio, the disk machine structure provides excellent cooling, thus permitting the use of a higher specific electric loading. Core loss, cogging torque, and magnetic pull between the stator and rotor are all eliminated by using this machine configuration.

Fig. 3 shows a form of HAWT for driving the proposed outer-rotor AFPMSG. Designed by Hunt [2], this turbine has recently received attention for possible deployment in a roof-top wind generation system. The turbine consists of a circular disk that spins on a stationary shaft. The sail-like rotatable shutters, when driven into the wind, will open to capture the wind energy, causing the circular disk to spin about the hollow shaft (shown shaded), hence turning the AFPMSG rotor mounted on the disk. The shutters are blown close when they move out of the wind, thus reducing the drag resistance.

Besides the above novel form of VAWT, the proposed AFPMSG can also be integrated with conventional turbine designs, such as the H-Darrieus turbine or the Savonius turbine [14]. Fig. 2 shows an arrangement in which the outer-rotor AFPMSG is mounted on the structure that supports the blades of an H-Darrieus turbine.

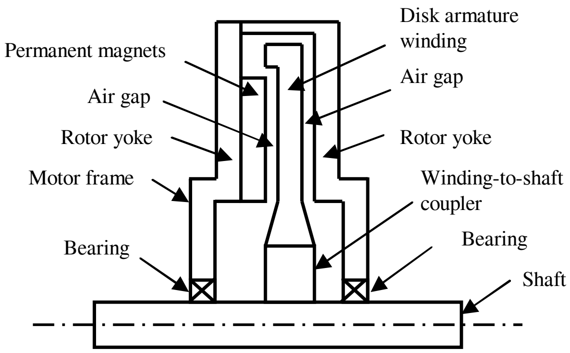


Fig. 1 Cross-sectional view of the proposed outer-rotor AFPMSG.

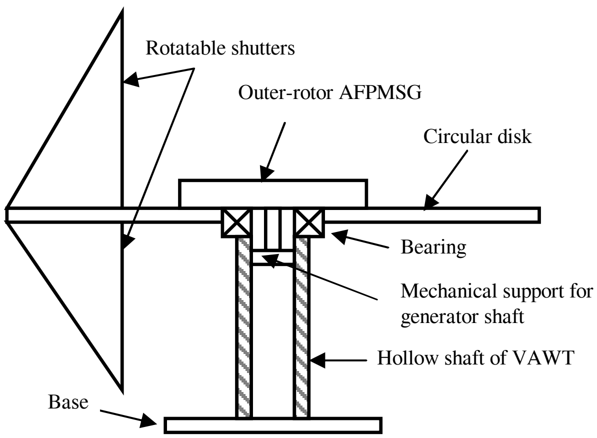


Fig. 2 A vertical-axis wind turbine (VAWT) driving an outer-rotor AFPMSG.

Fig. 3 shows an alternative method of installing the AFPMSG for an H-Darrieus turbine. The advantages of this arrangement include easy access to the generator for maintenance and shorter cables, but a long, heavy, and rigid shaft is required. and an inner rotor configuration will normally have to be used.

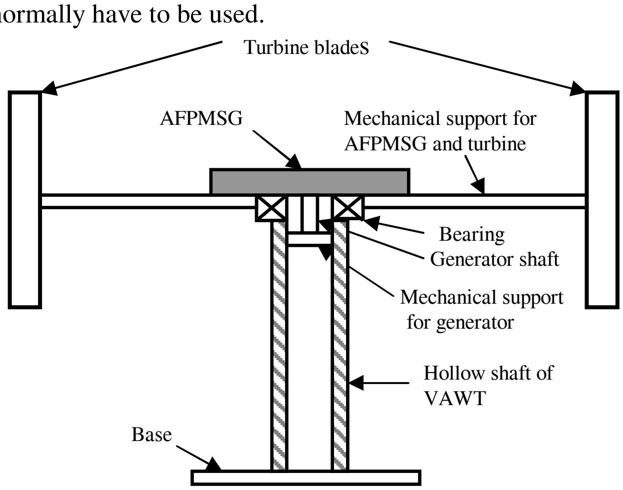


Fig. 3 AFPMSG direct-coupled to H-Darrieus turbine: inner-rotor AFPMSG mounted at ground level.

IV. Performance Evaluation

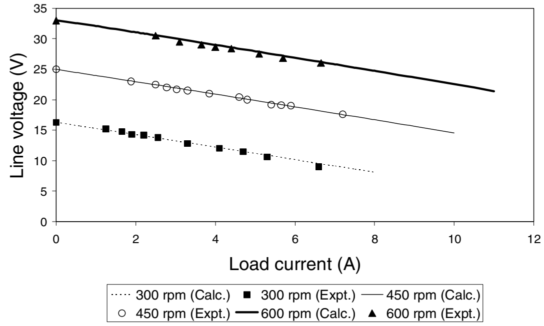
Fig. 4 shows the setup for experimental investigations on the AFPMSG. The shaft of the machine was mounted on a special test rig so that the rotor frame can turn freely. The generator rotor was coupled to a d.c. motor drive via a belt transmission. The turbine was therefore emulated by varying the speed of the d.c. motor.

The synchronous impedance Z_s of the AFPMSG was measured to be (0.58 + j0.25) Ω. at 450 r/min (or 60 Hz). Due to the large effective air gap, armature reaction is relatively weak in the AFPMSG and hence the synchronous reactance X_s is small compared with the armature resistance R. The voltage regulation therefore depends primarily on R in this type of machine.

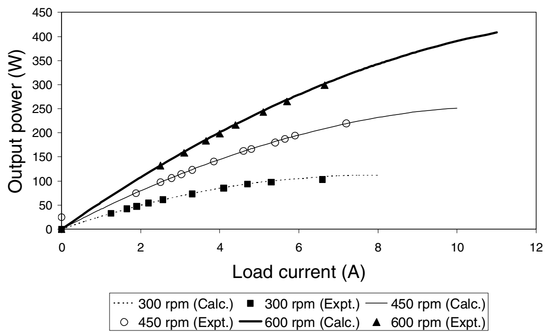
Figs. 5(a) to 5(c) show the variations of terminal voltage, output power, and efficiency of the experimental AFPMSG with line current under constant-speed operation. The voltage-current characteristics are practically linear from no load to full load. At a speed of 600 r/min, the voltage drop between no load and full load is 25% and an output power of 340 W can be delivered at rated current. When the speed is reduced to 300 r/min, the voltage drop between no load and full load increases to 50%, and at rated current the output power is only 110 W. Due to the relatively large armature resistance, maximum efficiency of the machine occurs at low values of load current. A maximum efficiency of 79.0% can be achieved at 600 r/min.

Figs. 6(a) and 6(b) show, respectively, the line voltage waveforms of the AFPMSG at no load and when delivering a current of 6.1 A to a resistive load. The waveforms are practically sinusoidal. From a measurement using a harmonic analyzer, it was found that in each case there was mainly a 1.4% 5th harmonic and a 0.2% 7th harmonic, with a total harmonic distortion of 1.6%. The voltage waveforms show that the proposed AFPMSG is an excellent source of sinusoidal power. The measurements also revealed that the total harmonic distortion was not sensitive to the variation of load. This is due to the fact that the armature reaction m.m.f. has only a slight effect on the resultant flux density distribution in the air gap.

Fig. 4 Prototype AFPMSG and test-ring.



(a)



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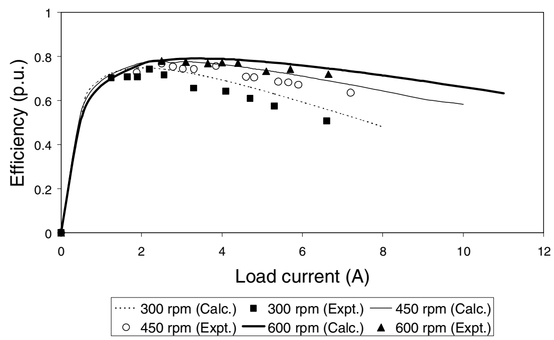
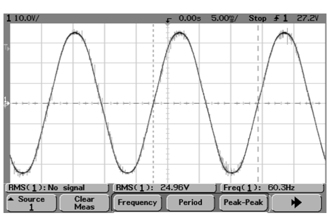
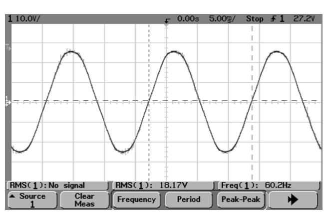


(c)

Fig. 5 Performance of AFPMSG under constant-speed operation.
(a) Variation of voltage with current;
(b) Variation of output power with current;
(c) Variation of efficiency with current.



(a)



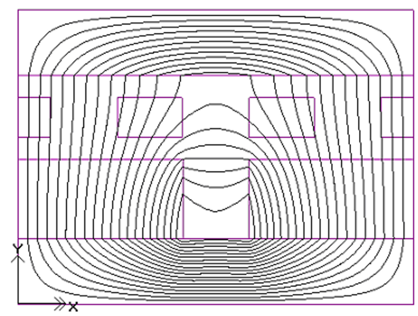
(b)

Fig. 6 Line voltage waveforms of AFPMSG (a) at no load; (b) when delivering a current of 6.1 A to a resistive load (Voltage scale: 10 V/div; time scale: 5 ms/div).

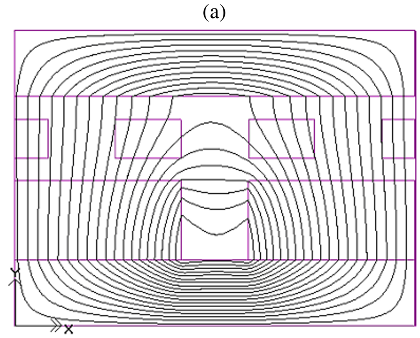
V. Magnetic Field Analysis

Analysis of the magnetic field in the proposed AFPMSG presents an interesting problem. Strictly speaking, the magnetic field distribution in an AFPMSG can only be accurately determined by solving a three-dimensional field problem, which involves difficult mathematics, complex programming efforts and long solution time. With a low-speed directly-coupled AFPMSG with a large number of poles, however, curvature effect may be ignored and the solution can be obtained more conveniently from a two-dimensional solution, based on a model set up in a cylindrical cutting plane at the mean radius. Both finite element method (FEM) [15] and analytical methods [16-17] have been used to study the field distribution of the AFPMSG. For computing the radial variation of the magnetic field, a quasi-three-dimensional analysis may be carried out by consider cylindrical cutting planes of different radii

Figs. 7a and 7b show the computed flux plot of the prototype AFPMSG on no load and full load at unity power factor, respectively [15]. It is observed that the air gap flux density in general has an axial component B_y as well as a circumferential component B_x. The flux plot also reveals that there is considerable leakage flux between adjacent magnetic poles. Besides, the flux lines are most dense in the bottom rotor yoke on which the magnets are mounted. As shown in Fig. 7a, the flux density in the bottom yoke (at y = 4.8 mm) reaches 1.8 T.



(a)



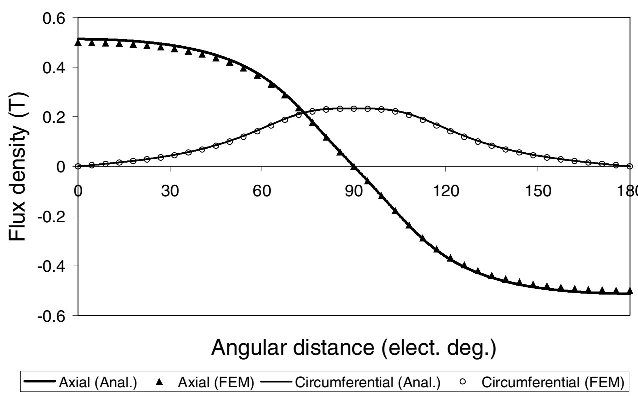
(b)

Fig. 7 Flux plots of AFPMSG: (a) no load; (b) full load at unity power factor.

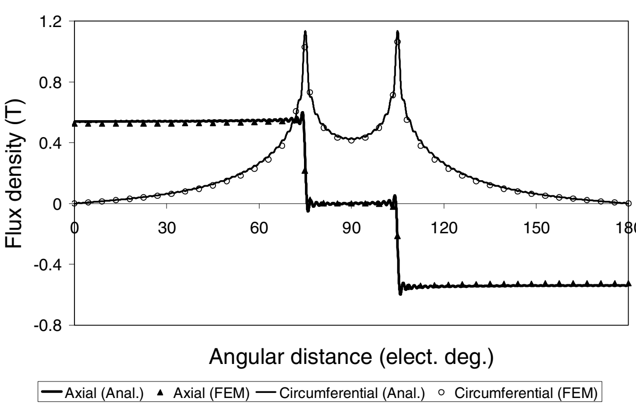
Due to the relatively long effective air gap, armature reaction effect is suppressed and the flux density distribution of the AFPMSG at full load differs only slightly from that at no load, as observed from Figs. 7a and 7b. The air gap flux density, leakage flux, and saturation level of the generator are thus primarily determined by the rotor magnetization, and these do not vary significantly with normal load current.

The no-load and armature reaction fields of the AFPMSG were also computed using a two-dimensional analytical method [16]. Laplace's equation was solved in the rectangular coordinate system to give the scalar magnetic potentials, using a Fourier series method. For computation of the armature reaction field, a multi-current-sheet model was employed in order to account for the distributed nature of armature conductors in the axial direction. The resultant magnetic field was then obtained by applying the principle of superposition. From Fig. 8(a) to Fig. 8(c), it is observed that the analytical results agree very well the FEM results. The analytical results give slightly higher field values, but in general the errors are within 3% of the computed results from FEM, thus validating the proposed analytical field computation method. Fig. 8(c) also confirms that the composite field due to magnets and armature reaction can be predicted by using a two-dimensional analytical model.

If only the air gap field is considered, a three-dimensional field solution is possible by using the concept of magnetic charges and method of images [17]. The method is computationally efficient and yields results that cannot be obtained from the method based on the two-dimensional solution of Laplace's equation. Of particular interest is the radial variation of the axial component of air gap flux density B_y. As shown in Fig. 9, B_y decreases to a very low value at the inner and outer circumference of the AFPMSG. Between the inner and outer circumference, there is also a gradual change in flux density. Fig. 10 shows the computed and experimental variations of B_y with radial distance. It is seen that the flux density is highest at a radial position between 0.085 m and 0.09 m, which is closer to the outer circumference. Agreement between measured and computed flux densities is quite satisfactory. The results show that a 2-D analysis may not be adequate for analyzing an AFPMSG.



(a)



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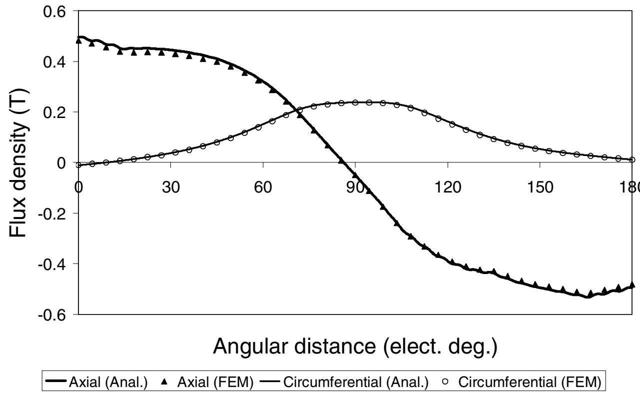

(c)

Fig. 8 Comparison of results computed using analytical method and FEM:
(a) No load flux density components at $y = 9.2$ mm
(b) No-load flux density components at $y = 6$ mm
(c) Flux density components at $y = 9.2$ mm when AFPMSG is under steady-state three-phase short-circuit at 450 r/min.

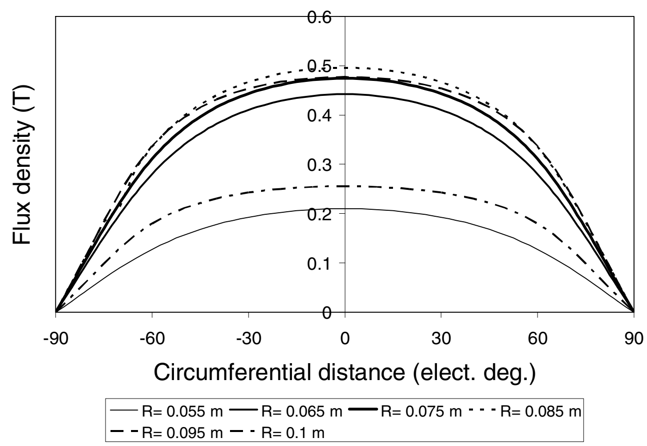

Fig. 9 Computed circumferential variations of flux density at $z = 0.002$ m.

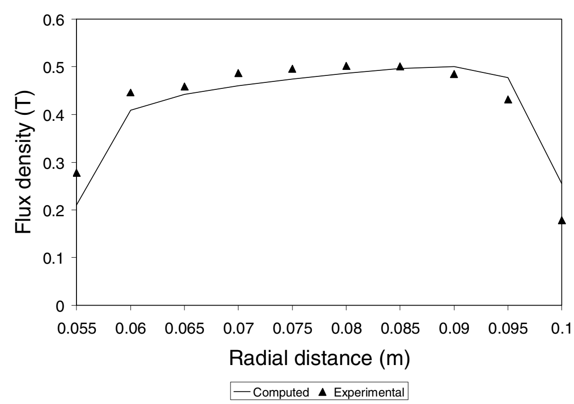

Fig. 10 Measured and computed variation of flux density with radial distance ($z = 0.002$ m).

VI. CONCLUSION

This paper has presented a novel form of wind energy system suitable for the urban environment. High efficiency is achieved by the use of an axial-flux permanent-magnet synchronous generator. Tests on a small prototype generator have demonstrated the feasibility of the system. Advanced magnetic field analyses using 2-D FEM and analytical methods provide useful information on the field distribution, providing guidelines on future machine design.

Acknowledgment

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T. F. Chan (M '95) received the B.Sc. (Eng.) and M.Phil. degrees in electrical engineering from the University of Hong Kong, Hong Kong, China, in 1974 and 1980, respectively. He received the PhD degree in electrical engineering from City University, London, UK, in 2005. Currently, Dr. Chan is an Associate Professor at the Department of Electrical Engineering, the Hong Kong Polytechnic University, Hong Kong, China, where he has been since 1978. His research interests are self-excited a.c. generators, brushless a.c. generators, and permanent-magnet machines. In June 2006, he was awarded a Prize Paper by IEEE Power Engineering Society Power Generation and Energy Development Committee. In 2007, Dr. Chan co-authored a book entitled *Distributed Generation - Induction and Permanent Magnet Generators*.

L. L. Lai (SM'92, F'07) received the B.Sc. (First Class Honors) and the Ph.D. degrees from the University of Aston in Birmingham, UK, in 1980 and 1984, respectively. In 2005, he was also awarded a D.Sc. degree by City University, London, UK.

Currently he is the Head of Energy Systems Group at City University, London, UK. He is a Visiting Professor at Southeast University, Nanjing, China and also a Guest Professor, Fudan University, Shanghai, China. He has authored/co-authored over 200 technical papers. He is the author of the book *Intelligent System Applications in Power Engineering—Evolutionary Programming and Neural Networks* and the editor of *Power System Restructuring and Deregulation—Trading, Performance and Information Technology*. In 2007, Dr. Lai co-authored a book entitled *Distributed Generation - Induction and Permanent Magnet Generators*. His professional activities include his contributions to several international conferences in power engineering and evolutionary computing,

Dr. Lai was awarded the IEEE Third Millennium Medal, 2000 IEEE Power Engineering Society UKRI Chapter Outstanding Engineer Award and 2003 IEEE Power Engineering Society Outstanding Large Chapter Award. In June 2006, he was awarded a Prize Paper by IEEE Power Engineering Society Power Generation and Energy Development Committee. He was the Conference Chair of the IEEE/IEE International Conference on Power Utility Deregulation, Restructuring and Power Technologies 2000. In 1995, he received a high-quality paper prize from the International Association of Desalination, USA.