



Full paper



Magnetic switch structured triboelectric nanogenerator for continuous and regular harvesting of wind energy

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ARTICLE INFO

Keywords:

Triboelectric nanogenerator
Wind energy harvesting
Magnetic switch
Continuous and regular output
Critical speed

ABSTRACT

From the extensive research on wind energy harvesting, the triboelectric nanogenerator (TENG) has proven to be effective in converting mechanical energy into electric energy. To supply continuous and regular electric energy above the critical speed, we developed a magnetic switch structured triboelectric nanogenerator (MS-TENG) consisting of transmission gears, energy modulation modules, and a generation unit. When wind falls intermittently on the wind scoop, the energy stored and released by the energy modulation modules at any time does not depend on wind speed but on the magnetic force of the magnets, enabling the wind energy to be converted into continuous and regular electric energy. The experimental results demonstrate that the MS-TENG can operate as a power supply, producing output characteristics of 410 V, 18 μ A, 155 nC, and a peak power of 4.82 mW, sufficient to power 500 LEDs in series or a thermometer. Its prospects in the field of wind energy harvesting appear excellent.

1. Introduction

The rapid development of the world economy has resulted in an excessive dependence on and consumption of energy derived from fossil fuels, that has led to a crisis in energy demands and environmental pollution [1–4]. Being a clean and renewable energy resource, wind energy is considered as an alternative to fossil fuels because of its unlimited supply, world-wide generation, and non-polluting aspect [5–9]. Therefore, there is a need to design wind power generators that provide constant and reliable supply but that are inexpensive and compact.

Triboelectric nanogenerator (TENG, also called as Wang generator [10]) was first invented by Wang's group in 2012 [11]. It produces displacement current as the driving force to convert mechanical energy into electric power/signal [12] by the coupling effect of contact electrification and electrostatic induction [13,14]. Its unique merits are low cost, easy fabrication, diverse choice of materials, and wide range of applications [15–17]. TENGs have been designed to harvest various natural energies such as wind energy [18–22], blue energy [23–26],

vibrational energy [27,28], acoustic wave energy [29], energy from rainfall [30], and biomechanical energy [31–34]. To improve the harvesting of mechanical energy from the natural environment, many mechanical modes of TENGs have been designed that include features such as machinery frequency enhancement [23,35,36], intermittent energy harvesting [31,37], and mechanical regulation [27,38]. In particular, TENGs with a mechanical regulation mode can convert random mechanical energy into a controllable source of electrical energy. However, the outputs of these TENGs are intermittent, making them incapable powering electrical devices continuously. Therefore, to harvest mechanical energy from a random resource, TENG with a continuous and regular output performance needs to be designed.

For this purpose, a magnetic switch structured triboelectric nanogenerator (MS-TENG) was proposed for harvesting of wind energy. The kinetic energy of wind captured by the wind scoop is converted into magnetic potential energy via transmission gears and energy modulation modules, which drives the generation unit to operate. The critical speed of the MS-TENG was studied systematically. When the input speed

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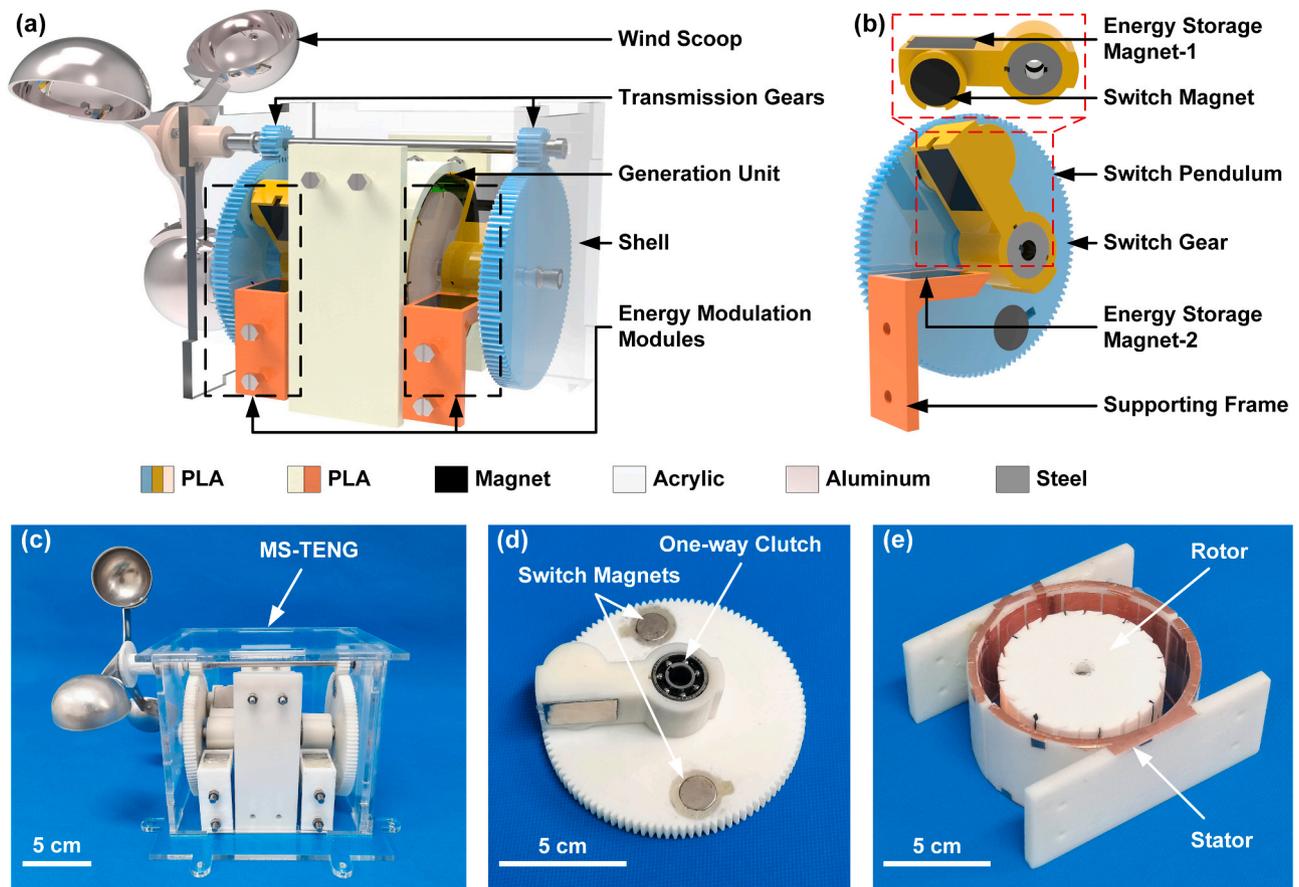


Fig. 1. The magnetic switch structured triboelectric nanogenerator (MS-TENG): (a) schematic diagram of the overall structure, (b) the left energy modulation module; (c-e) photographs of the MS-TENG, the switch gear and switch pendulum, and the generation unit.

exceeds the critical speed, the MS-TENG outputs a continuous and regular supply of electric energy. Experimental results show that the MS-TENG has output characteristics of 410 V, 18 μ A, 155 nC and a peak power of 4.82 mW, sufficient to power 500 LEDs in series or a thermometer, all indications suggest its prospects in wind energy harvesting excellent.

2. Results and discussion

2.1. Structural design and operation principle

The overall structure of the magnetic switch structured triboelectric nanogenerator (MS-TENG) is shown in Fig. 1a, which includes the wind scoop, transmission gears, energy modulation modules, and generation unit. Wind energy is captured with the assistance of the wind scoop. The energy modulation modules and generation unit operate together to convert wind energy into electric energy. The energy modulation module includes a switch gear, a switch pendulum, a supporting frame, a one-way clutch, two pairs of switch magnets, and a pair of energy storage magnets (Fig. 1b). The photo of the MS-TENG is shown in Fig. 1c. Fig. 1d shows the switch gear and switch pendulum. The generation unit includes a rotor and a stator, as depicted in Fig. 1e.

Fig. 2a shows the operating principle of the MS-TENG. The kinetic energy of the wind is converted into mechanical energy of rotation by the wind scoop, which rotates the switch gears via transmission gears. In sequence, beginning with Fig. 2a(i), the left energy modulation module is in the energy storage state. The attraction from the switch magnets forces magnet-1 to swing closer to magnet-2, thereby increasing the repulsion between these two energy storage magnets. The right energy modulation module is also in the energy storage state. In Fig. 2a(ii), the

left energy modulation module is in the triggering state, its two energy storage magnets being in mutual contact. The right energy modulation module remains in the energy storage state. In Fig. 2a(iii), the right energy modulation module is still in the energy storage state. The left supporting frame forces the switch magnets to separate. The switch pendulum bounces and rotates because of the repulsion between the energy storage magnets, forcing the rotor of the generation unit to rotate. The films of fluorinated ethylene propylene (FEP) and the copper electrodes slide relatively to produce electric energy. As shown in Fig. 2a(iv), the right energy modulation module is in the triggering state and the left energy modulation module is in the energy storage state. In Fig. 2a(v), the right energy modulation module drives the rotor to rotate and the electric energy is obtained, while the left energy modulation module is still in the energy storage state.

The power generation principle of the generation unit is shown in Fig. 2b. In Fig. 2b(i), the FEP film is in full contact with copper-1. Based on triboelectrification, electrons in copper-1 are injected into the FEP film. Therefore, equal amounts of positive and negative charges accumulate on the surfaces of copper-1 and the FEP film, respectively. Next the FEP film slides from copper-1 to copper-2 and is in concurrent contact with both coppers [Fig. 2b(ii)]. Electrons in copper-2 flow into copper-1 through an external circuit. The FEP film then comes in full contact with copper-2 [Fig. 2b(iii)]. Once more, equal amounts of positive and negative charges accumulate on the surfaces of copper-2 and the FEP film. Finally, the FEP film slides from copper-2 to copper-1, again in concurrent contact with both coppers [Fig. 2b(iv)]. Electrons from copper-1 flow into copper-2 through an external circuit, and completing a single cycle of electron transfers.

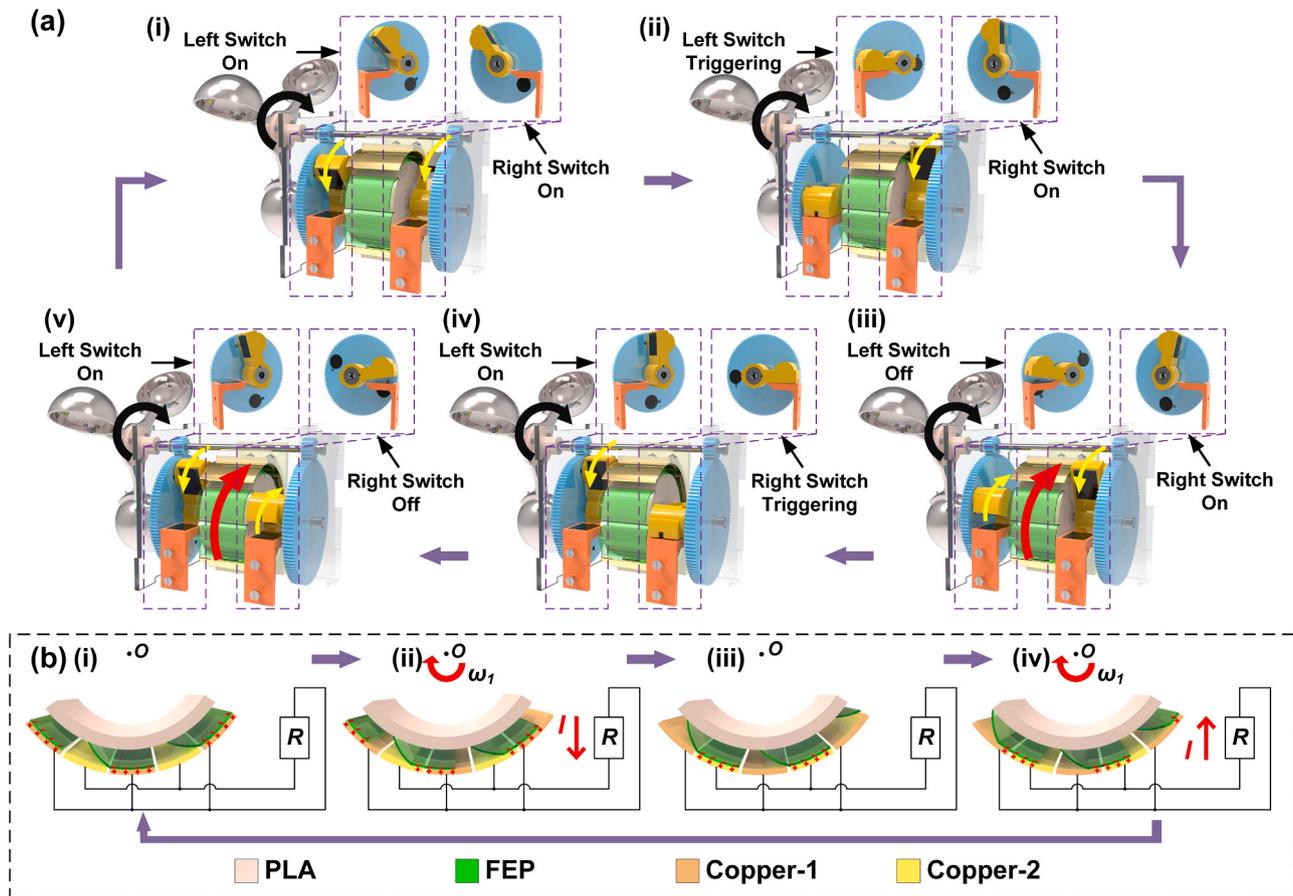


Fig. 2. Schematics of the operating principle of the MS-TENG: (a) sequence of different working states, (b) schematic illustrating the principle of power generation.

2.2. Performance

Using a stepper motor as excitation source, we investigated the basic performance of the MS-TENG. The configuration of the FEP film and rotor (Fig. S2, Supporting Information) indicates that a deformation of the FEP film occurs through pressure from the copper electrode. To study the dependence of output performance on the diameter of the switch magnets and rotor mass, five rotor masses and three diameters of the switch magnets were selected for the experiments, as shown in Fig. 3. A pair of switch magnets was mounted in the left energy modulation module; no switch magnets were installed in the right energy modulation module.

Nomenclature

F_b	repulsion generated by the energy storage magnets.
θ	switch angle of the MS-TENG.
T	initial torque of the MS-TENG.
N	number of generations for one rotation of the switch gear.

With increasing rotor mass, the open-circuit voltage [Fig. 3a(i), b(i) and c(i)] and the transferred charge [Fig. S3a(i), b(i) and c(i), Supporting Information] remain constant, whereas the short-circuit current [Fig. 3a(ii), b(ii) and c(ii)] and the load current through the external resistance of 50 M Ω resistance decrease [Fig. S3a(ii), b(ii), and c(ii), Supporting Information]. From calculations, with increasing rotor mass, the rotation period of the rotor increases, and the power and energy at the output decrease during one generation cycle (Fig. 3d, e, and f). From a calculation, the rotation period, output power, and output energy for switch magnets of diameter 15 mm and 20 mm are approximately equal, but larger than for the 10-mm-diameter switch magnets. When any of the switch magnets are separated, the repulsion F_b generated by the energy storage magnets is 5.31 N, 11.95 N and 12.29 N, in order of increasing diameter (Table S2, Supporting Information), which leads to

their output performance. In addition, from calculations, the initial torque T of the 15-mm switch magnets is 0.48 N·m, which is smaller than the 0.85 N·m torque for the 20-mm switch magnets. Therefore, with the 15-mm switch magnets, the MS-TENG is easier to operate at low wind speeds than one with 20-mm magnetic switches (see Supporting Information for details). The better output performance is seen in the MS-TENG, with 15-mm switch magnets and a rotor mass of 85 g.

In addition to varying the diameter of the switch magnets and the mass of the rotor, the distribution of the switch magnets in the energy modulation modules also affects the output performance of the MS-TENG. Further experiments were performed with different distributions of the switch magnets as well as input speeds. The distributions are classified $L_i R_j$, where i and j are the number of switch magnets in the left and right energy modulation modules, respectively. Typical distributions are L1R0, L1R1, L2R0 and L2R2, [Fig. 4a(i), b(i), c(i) and d(i)]. The switch angle θ and the number of generations N for one rotation of the switch gear are determined by the different distributions of switch magnets (see listing in Table 1).

With increasing input speed, the open-circuit voltage [Fig. 4a(ii), b(ii), c(ii) and d(ii)] and transferred charge (Fig. S4a, b, c and d, Supporting Information) remain unchanged, whereas the short-circuit current [Fig. 4a(iii), b(iii), c(iii) and d(iii)] increases. After the switch magnets separate, the switch magnet in the switch gear moves away faster from the magnet in the switch pendulum with higher input speeds. The attraction of the switch magnets decreases rapidly, which results in the switch pendulum bouncing and rotating faster. Hence, a higher short-circuit current is obtained.

Moreover, with increasing input speed, the output performance of the MS-TENG changes from intermittent stage to continuous stage. When the switch magnets remain the same, the same repulsion generated by the energy storage magnets forces the switch pendulum to

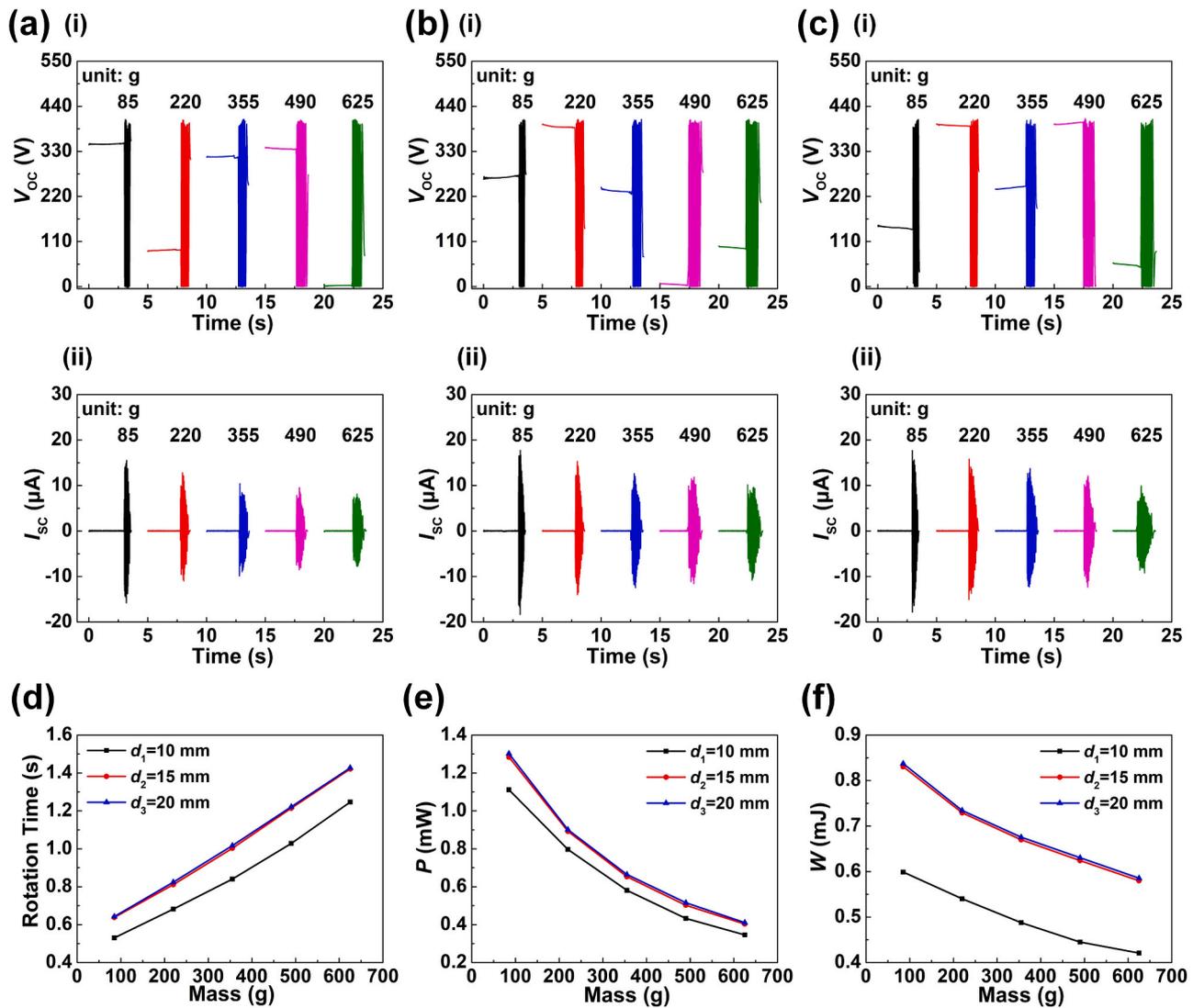


Fig. 3. Rotor mass dependence of the output performance of the MS-TENG with different diameter of switch magnets: (a) 10 mm diameter, (b) 15 mm diameter, (c) 20 mm diameter; comparisons of (d) rotation period, (e) output power, and (f) output energy against rotor mass for the different diameters of switch magnets.

bounce, initiating the rotor to rotate at a specific initial speed, thereby producing a regular output performance. An increase in input speed, reduces the interval time between two power generations. When the input speed reaches the critical speed, the interval time disappears and the rotor rotates continuously. In the sequence given in Fig. 4, the critical speed for each distribution of magnet is 560 r/min, 340 r/min, 340 r/min and 230 r/min. The distribution L2R2 has the lowest critical speed, and hence the MS-TENG attains more easily a continuous and regular electric output at low wind speeds.

To study the steadiness of the output performance of the MS-TENG under different working conditions further, comparative experiments were performed under different input patterns, as shown in Fig. 5. No matter how each pattern changes, the open-circuit voltage, short-circuit current and transferred charge are regular, although micro-vibrations may cause slight fluctuations in output performance during operations. Indeed, when the input speed does not reach the critical speed, the output performance of the MS-TENG is intermittent but regular. Once the critical speed is reached, the output performance becomes continuous and regular.

2.3. Demonstration

The charging performance of five commercial capacitors of 4.7 μF ,

10 μF , 22 μF , 47 μF and 100 μF was obtained (Fig. 6a). The load voltage and load current were measured under different load resistances, as shown in Fig. 6b. With increasing load resistance, load voltage increases and load current decreases. From calculations, the peak power of the MS-TENG was 4.82 mW with a 50 M Ω load resistance. Furthermore, experiments mimicking wind energy harvesting were conducted to testify the output performance. With the assistance of a bridge rectifier, the MS-TENG was able to harvest wind energy to supply power to 500 LEDs in series simultaneously (Movie S1, Supporting Information). We also developed a test system in which the wind-energy-harvesting MS-TENG ran a thermometer (Fig. 6d). After charging the capacitor for a period of time, the MS-TENG was able to power the thermometer normally (Movie S2, Supporting Information). Prospects for applications of the MS-TENG in the field of wind energy harvesting appear good.

Supplementary material related to this article can be found online at [doi:10.1016/j.nanoen.2021.105851](https://doi.org/10.1016/j.nanoen.2021.105851).

3. Conclusions

In summary, we described a magnetic switch structured triboelectric nanogenerator (MS-TENG) producing continuous and regular output while harvesting wind energy. The test experiments conducted prove that with input speeds above a critical speed, the electric output is

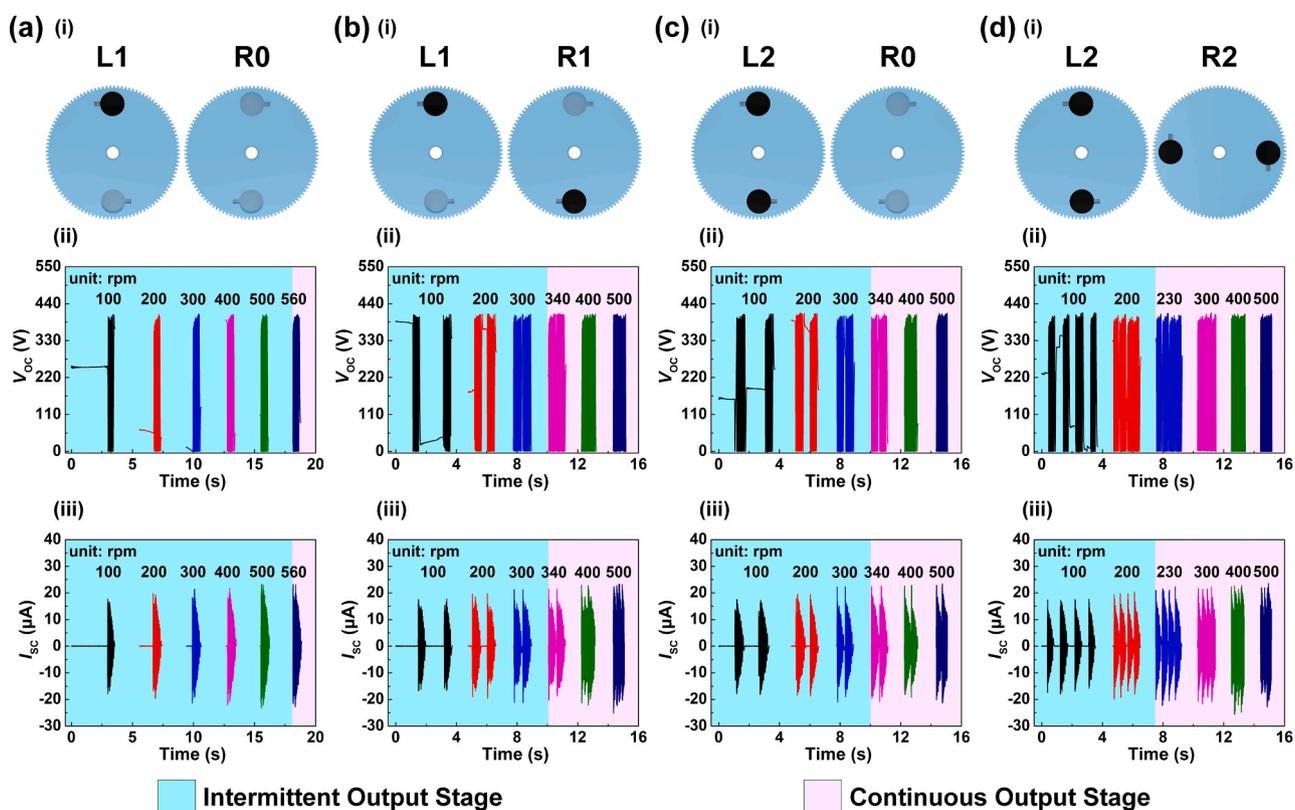


Fig. 4. Dependence of output performance on input speeds for the MS-TENG with different distributions of switch magnets: (a) L1R0, (b) L1R1, (c) L2R0, and (d) L2R2.

Table 1

Switch angle and number of generations for one rotation of the switch gear.

	L1R0	L1R1	L2R0	L2R2
θ ($^{\circ}$)	360	180	180	90
N	1	2	2	4

continuous and regular. Working under variable and irregular conditions, the MS-TENG produced an output performance with an open-circuit voltage of 410 V, a short-circuit current of 18 μ A, a transferred charge of 155 nC and a peak power of 4.82 mW. The MS-TENG powered 500 LEDs in series and a thermometer, demonstrating that the prospects applications of the MS-TENG in wind energy harvesting are good. The benefits in its design in converting wind energy into a reliable electric output may provide helpful guidance in wind harvesting for the future.

4. Experimental section

4.1. Fabrication of the MS-TENG

The magnetic switch structured triboelectric nanogenerator (MS-TENG) has dimensions of 200 mm (length) \times 125 mm (width) \times 150 mm (height). The shell is made from an acrylic material and fabricated by laser cutting. The transmission gear, switch gear, switch pendulum, supporting frame and generation unit were all 3D printed, the print material being polylactic acid (PLA). The switch and energy

storage magnet are made of neodymium. Made of stainless steel, the shaft was machine lathed. The flexible films (thickness 100 μ m and width 40 mm) are made of fluorinated ethylene propylene (FEP). The sixteen copper electrodes (thickness 65 μ m, width 18 mm and length 40 mm) were uniformly distributed on the inner wall of the stator. Additional information is available in [Supporting Information](#).

4.2. Electrical measurement

Rotating mechanical energy output by a two-phase hybrid stepping motor (57BYGH56D8EIS-P, HOHI, China) is used to power MS-TENG. The output signal of the generator is harvested by an electrometer (6514, Keithley, USA) and converted by a data acquisition system (USB-6218, National Instruments, USA). The display and storage of data is performed by installing the software LabVIEW with the computer.

CRediT authorship contribution statement

Shiming Liu: Conceptualization, Investigation, Writing - original draft. **Xiang Li:** Investigation, Writing - original draft, Validation. **Yuqi Wang:** Investigation, Validation. **Yanfei Yang:** Investigation. **Lixia Meng:** Conceptualization, Resources, Writing - review & editing, Supervision. **Tinghai Cheng:** Conceptualization, Resources, Writing - review & editing, Supervision. **Zhong Lin Wang:** Conceptualization, Resources, Writing - review & editing, Supervision.

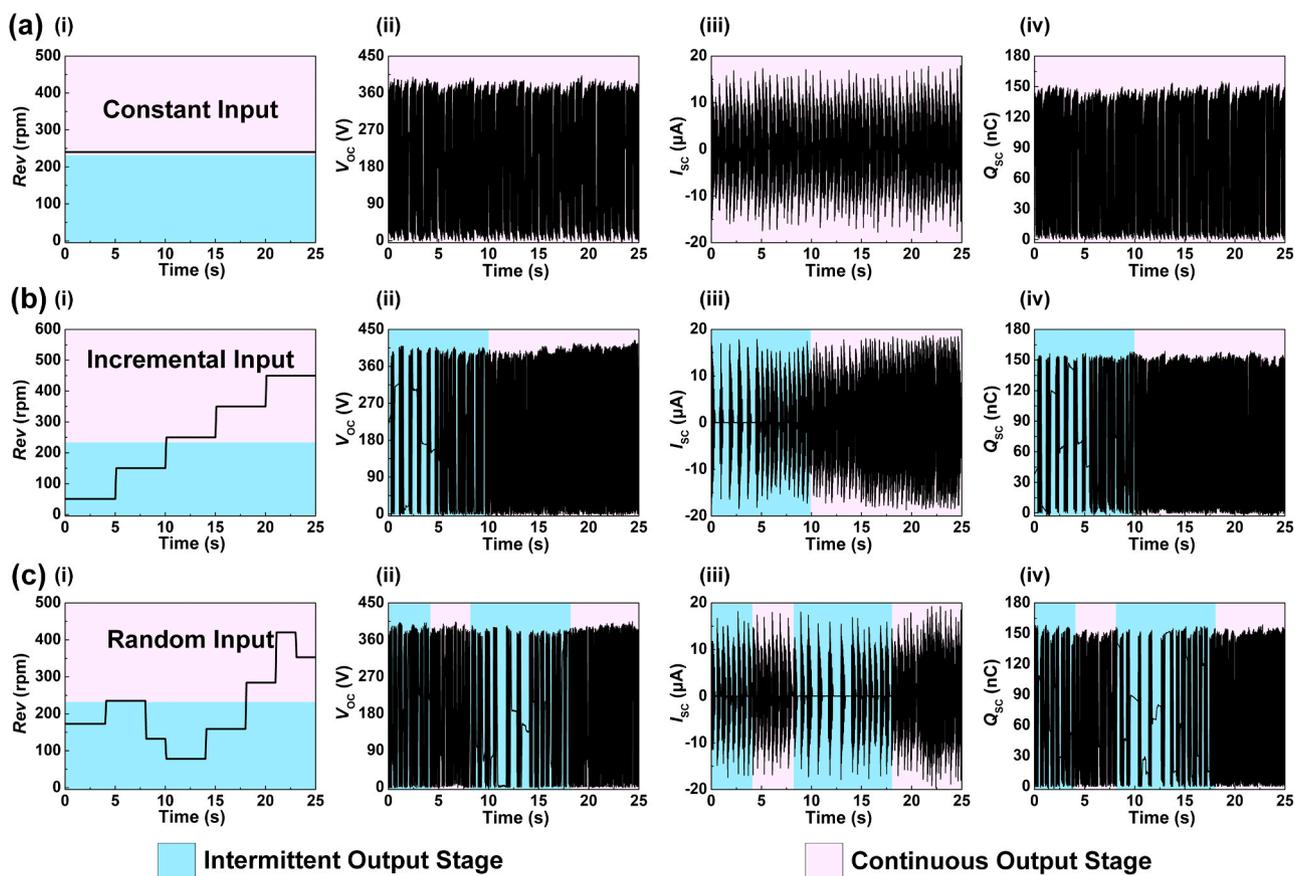


Fig. 5. Output performance of the MS-TENG from different excitation inputs: (a) constant input, (b) stepwise incremental input, (c) random step input.

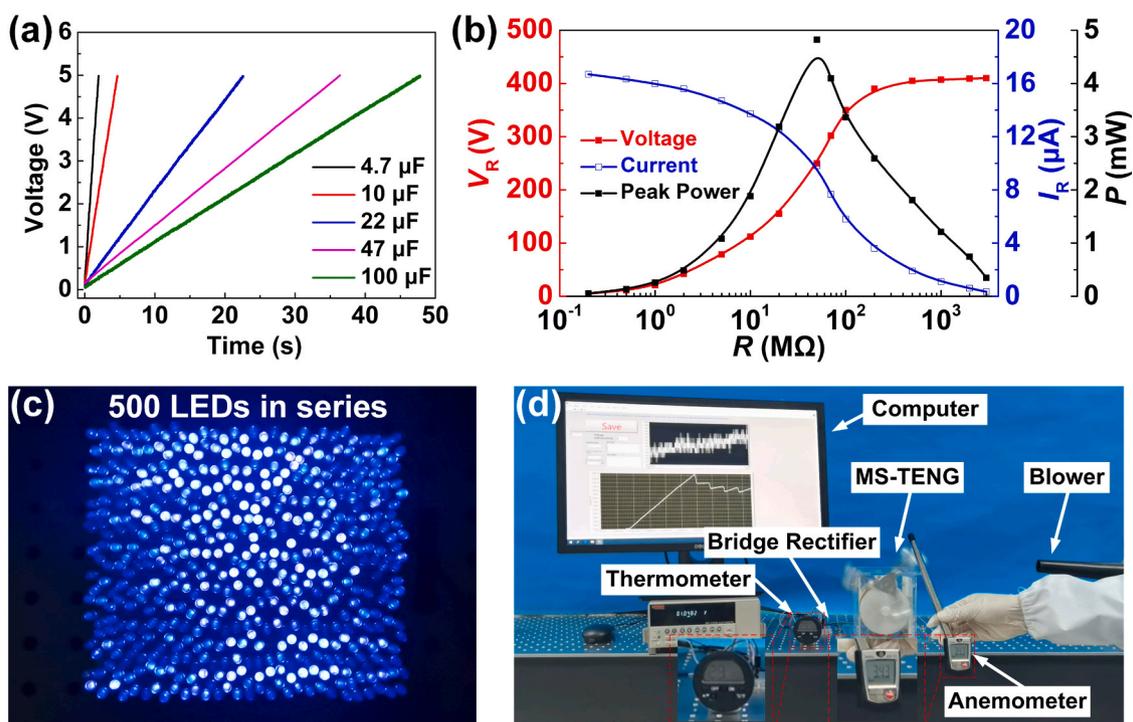


Fig. 6. Demonstrating the performance of the MS-TENG: (a) charging different commercial capacitors, (b) load voltage, load current and peak power of the MS-TENG, (c) the MS-TENG running 500 LEDs in series, (d) experimental setup used in the MS-TENG powering a thermometer.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Shiming Liu, Xiang Li, Yuqi Wang contributed equally to this work. The authors are grateful for the support received from the National Natural Science Foundation of China (No. 51775130) and the National Key R&D Project from the Minister of Science and Technology (Nos. 2016YFA0202701 and 2016YFA0202704), the Beijing Municipal Science and Technology Commission (No. Z171100002017017).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.nanoen.2021.105851](https://doi.org/10.1016/j.nanoen.2021.105851).

References

- Z.L. Wang, Entropy theory of distributed energy for internet of things, *Nano Energy* 58 (2019) 669–672.
- Z.L. Wang, W. Wu, Nanotechnology-enabled energy harvesting for self-powered micro-/nanosystems, *Angew. Chem. Int. Ed.* 51 (2012) 11700–11721.
- Z.L. Wang, Triboelectric nanogenerators as new energy technology and self-powered sensors - principles, problems and perspectives, *Faraday Discuss.* 176 (2014) 447–458.
- B. Chen, Y. Yang, Z.L. Wang, Scavenging wind energy by triboelectric nanogenerators, *Adv. Energy Mater.* 8 (2018), 1702649.
- X. Zhao, D. Zhang, S.W. Xu, W.Q. Qian, W. Han, Z.L. Wang, Y. Yang, Stretching-enhanced triboelectric nanogenerator for efficient wind energy scavenging and ultrasensitive strain sensing, *Nano Energy* 75 (2020), 104920.
- Z.W. Ren, Z.M. Wang, Z.R. Liu, L.F. Wang, H.Y. Guo, L.L. Li, S.T. Li, X.Y. Chen, W. Tang, Z.L. Wang, Energy harvesting from breeze wind ($0.7\text{--}6\text{ m s}^{-1}$) using ultra-stretchable triboelectric nanogenerator, *Adv. Energy Mater.* 10 (2020), 2001770.
- D. Liu, B.D. Chen, J. An, C.Y. Li, G.X. Liu, J.J. Shao, W. Tang, C. Zhang, Z.L. Wang, Wind-driven self-powered wireless environmental sensors for Internet of Things at long distance, *Nano Energy* 73 (2020), 104819.
- J. Tian, X. Chen, Z.L. Wang, Environmental energy harvesting based on triboelectric nanogenerators, *Nanotechnology* 31 (2020), 242001.
- S.W. Cui, Y.B. Zheng, J. Liang, D.A. Wang, Triboelectrification based on double-layered polyaniline nanofibers for self-powered cathodic protection driven by wind, *Nano Res.* 11 (2018) 1873–1882.
- T. Jiang, H. Pang, J. An, P.J. Lu, Y.W. Feng, X. Liang, W. Zhong, Z.L. Wang, Robust swing-structured triboelectric nanogenerator for efficient blue energy harvesting, *Adv. Energy Mater.* 10 (2020), 2000064.
- F.-R. Fan, Z.-Q. Tian, Z. Lin Wang, Flexible triboelectric generator, *Nano Energy* 1 (2012) 328–334.
- Z.L. Wang, Triboelectric nanogenerator (TENG)—sparking an energy and sensor revolution, *Adv. Energy Mater.* 10 (2020), 2000137.
- H.Y. Zou, Y. Zhang, L.T. Guo, P.H. Wang, X. He, G.Z. Dai, H.W. Zheng, C.Y. Chen, A.C. Wang, C. Xu, W.Z. L., Quantifying the triboelectric series, *Nat. Commun.* 10 (2019), 1427.
- Z.L. Wang, On the first principle theory of nanogenerators from Maxwell's equations, *Nano Energy* 68 (2020), 104272.
- Z.L. Wang, Triboelectric nanogenerators as new energy technology for self-powered systems and as active mechanical and chemical sensors, *ACS Nano* 7 (2013) 9533–9557.
- Z.L. Wang, G. Zhu, Y. Yang, S.H. Wang, C.F. Pan, Progress in nanogenerators for portable electronics, *Mater. Today* 15 (2012) 532–543.
- W.Q. Liu, X. Wang, Y.X. Song, R.R. Cao, L.L. Wang, Z.G. Yan, G.Y. Shan, Self-powered forest fire alarm system based on impedance matching effect between triboelectric nanogenerator and thermosensitive sensor, *Nano Energy* 73 (2020), 104843.
- K. Han, J.J. Luo, Y.W. Feng, Q.S. Lai, Y. Bai, W. Tang, Z.L. Wang, Wind-driven radial-engine-shaped triboelectric nanogenerators for self-powered absorption and degradation of NO_x , *ACS Nano* 14 (2020) 2751–2759.
- J.J. Luo, Z.L. Wang, Recent advances in triboelectric nanogenerator based self-charging power systems, *Energy Storage Mater.* 23 (2019) 617–628.
- Y.M. Zhong, H.B. Zhao, Y.C. Guo, P.S. Rui, S.W. Shi, W. Zhang, Y.L. Liao, P. H. Wang, Z.L. Wang, An easily assembled electromagnetic-triboelectric hybrid nanogenerator driven by magnetic coupling for fluid energy harvesting and self-powered flow monitoring in a smart home/city, *Adv. Mater. Technol.* 4 (2019), 1900741.
- P.H. Wang, L. Pan, J.Y. Wang, M.Y. Xu, G.Z. Dai, H.Y. Zou, K. Dong, Z.L. Wang, An ultra-low-friction triboelectric-electromagnetic hybrid nanogenerator for rotation energy harvesting and self-powered wind speed sensor, *ACS Nano* 12 (2018) 9433–9440.
- Y.G. Feng, L.Q. Zhang, Y.B. Zheng, D.A. Wang, F. Zhou, W.M. Liu, Leaves based triboelectric nanogenerator (TENG) and TENG tree for wind energy harvesting, *Nano Energy* 55 (2019) 260–268.
- M.F. Yin, Y. Yu, Y.Q. Wang, Z. Wang, X.H. Lu, T.H. Cheng, Z.L. Wang, Multi-plate structured triboelectric nanogenerator based on cycloidal displacement for harvesting hydroenergy, *Extrem. Mech. Lett.* 33 (2019), 100576.
- X. Liang, T. Jiang, Y.W. Feng, P.J. Lu, J. An, Z.L. Wang, Triboelectric nanogenerator network integrated with charge excitation circuit for effective water wave energy harvesting, *Adv. Energy Mater.* 10 (2020), 2002123.
- S.X. Nie, H.Y. Guo, Y.X. Lu, J.T. Zhuo, J.L. Mo, Z.L. Wang, Superhydrophobic cellulose paper-based triboelectric nanogenerator for water drop energy harvesting, *Adv. Mater. Technol.* 5 (2020), 2000454.
- X. Wang, Z. Wen, H.Y. Guo, C.S. Wu, X. He, L. Lin, X. Cao, Z.L. Wang, Fully packaged blue energy harvester by hybridizing a rolling triboelectric nanogenerator and an electromagnetic generator, *ACS Nano* 10 (2016) 11369–11376.
- W.X. Yang, Q. Gao, X. Xia, X.S. Zhang, X.H. Lu, S.T. Yang, T.H. Cheng, Z.L. Wang, Travel switch integrated mechanical regulation triboelectric nanogenerator with linear–rotational motion transformation mechanism, *Extrem. Mech. Lett.* 37 (2020), 100718.
- C. Wu, H. Huang, S. Yang, G.J. Wen, Pagoda-shaped triboelectric nanogenerator with high reliability for harvesting vibration energy and measuring vibration frequency in downhole, *IEEE Sens. J.* 20 (2020) 13999–14006.
- H.F. Zhao, X. Xiao, P. Xu, T.C. Zhao, L.G. Song, X.X. Pan, J.C. Mi, M.Y. Xu, Z. L. Wang, Dual-tube helmholtz resonator-based triboelectric nanogenerator for highly efficient harvesting of acoustic energy, *Adv. Energy Mater.* 9 (2019), 1902824.
- M. Jošt, B. Lipovšek, B. Glazar, A. Al-Ashouri, K. Brecl, G. Matič, A. Magomedov, V. Getautis, M. Topič, S. Albrecht, Perovskite solar cells go outdoors: field testing and temperature effects on energy yield, *Adv. Energy Mater.* 10 (2020), 2000454.
- X.H. Lu, Y.H. Xu, G.D. Qiao, Q. Gao, X.S. Zhang, T.H. Cheng, Z.L. Wang, Triboelectric nanogenerator for entire stroke energy harvesting with bidirectional gear transmission, *Nano Energy* 72 (2020), 104726.
- Y.H. Chen, X. Pu, M.M. Liu, S.Y. Kuang, P.P. Zhang, Q.L. Hua, Z.F. Cong, W.B. Guo, W.G. Hu, Z.L. Wang, Shape-adaptive, self-healable triboelectric nanogenerator with enhanced performances by soft solid-solid contact electrification, *ACS Nano* 13 (2019) 8936–8945.
- B.D. Chen, W. Tang, T. Jiang, L.P. Zhu, X.Y. Chen, C. He, L. Xu, H.Y. Guo, P. Lin, D. Li, J.J. Shao, Z.L. Wang, Three-dimensional ultraflexible triboelectric nanogenerator made by 3D printing, *Nano Energy* 45 (2018) 380–389.
- L.L. Wang, W.Q. Liu, Z.G. Yan, F.J. Wang, X. Wang, Stretchable and shape-adaptable triboelectric nanogenerator based on biocompatible liquid electrolyte for biomechanical energy harvesting and wearable human-machine interaction, *Adv. Funct. Mater.* (2020), 2007221.
- T.H. Cheng, Y.K. Li, Y.-C. Wang, Q. Gao, T. Ma, Z.L. Wang, Triboelectric nanogenerator by integrating a cam and a movable frame for ambient mechanical energy harvesting, *Nano Energy* 60 (2019) 137–143.
- Q. Gao, Y.K. Li, Z.J. Xie, W.X. Yang, Z. Wang, M.F. Yin, X.H. Lu, T.H. Cheng, Z. L. Wang, Robust triboelectric nanogenerator with ratchet-like wheel-based design for harvesting of environmental energy, *Adv. Mater. Technol.* 5 (2019), 1900801.
- W.X. Yang, Y.Q. Wang, Y.K. Li, J.L. Wang, T.H. Cheng, Z.L. Wang, Integrated flywheel and spiral spring triboelectric nanogenerator for improving energy harvesting of intermittent excitations/trigging, *Nano Energy* 66 (2019), 104104.
- M.F. Yin, X.H. Lu, G.D. Qiao, Y.H. Xu, Y.Q. Wang, T.H. Cheng, Z.L. Wang, Mechanical regulation triboelectric nanogenerator with controllable output performance for random energy harvesting, *Adv. Energy Mater.* 10 (2020), 2000627.



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