Supporting Information

An Impeller-Actuated Triboelectric Nanogenerator with rotary Soft-Contact Separation mode for Wind Vector Sensing

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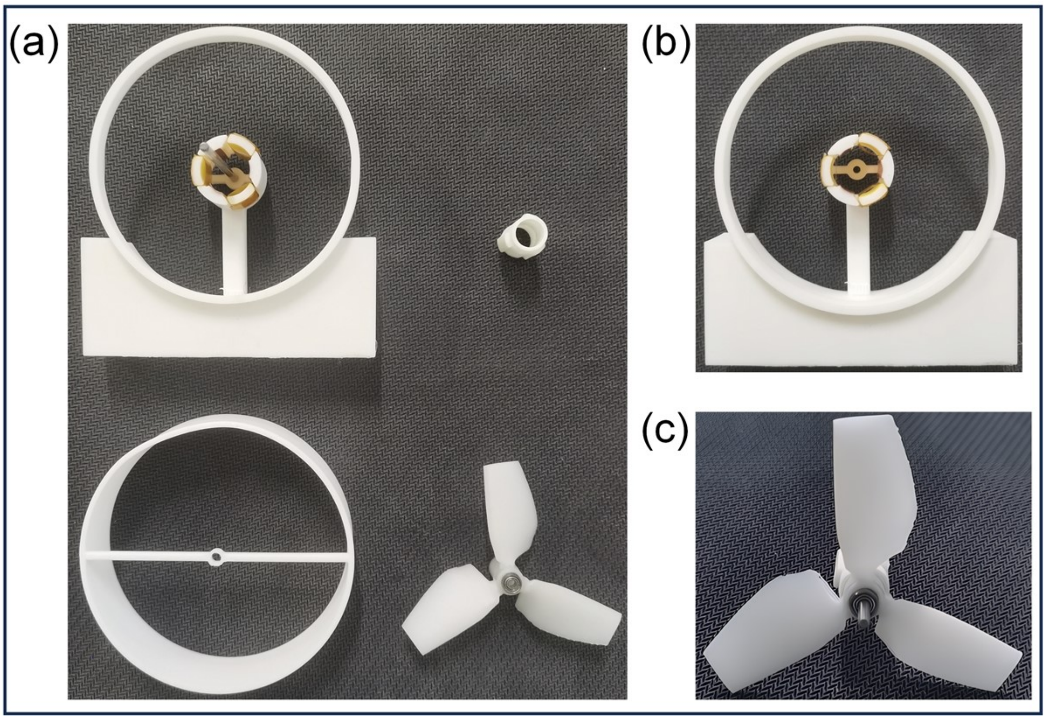


Figure S1. RSCS-TENG physical: (a) Parts overview;(b) Stator;(c) Rotor

Table S1. Chord length and torsion angle of blade element at each i_{TSR}

		Blade Element 1	Blade element 2	Blade element 3	Blade element 4	Blade element 5
i_{TSR} =1	chord length/mm	0.016218	0.024617	0.027615	0.027016	0.02286
	torsion angle/°	40.543743	33.149914	26.664803	21.025837	15.875525
i_{TSR} =2	chord length/mm	0.012728	0.015056	0.01385	0.011894	0.009588
	torsion angle/°	33.739352	22.668569	15.115824	9.82727	5.702348
i_{TSR} =3	chord length/mm	0.009884	0.009431	0.007664	0.006196	0.004947
	torsion angle/°	27.936846	15.605508	8.653618	4.334298	1.18199
i_{TSR} =4	chord length/mm	0.007676	0.006218	0.00471	0.003702	0.002958
	torsion angle/°	23.121976	10.794116	4.708506	1.175297	-1.312422

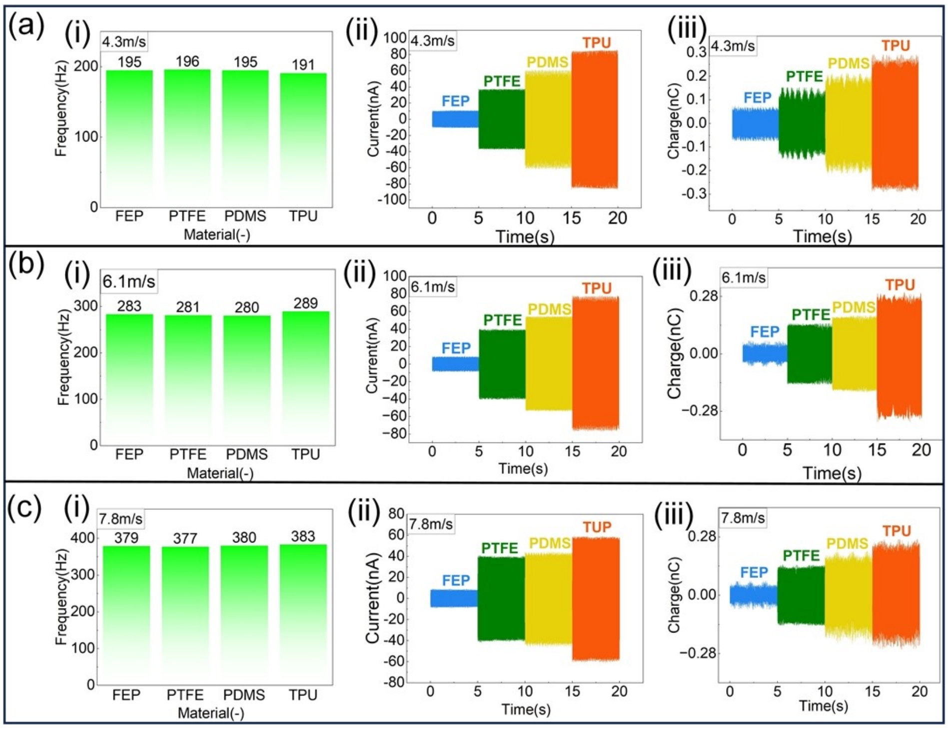
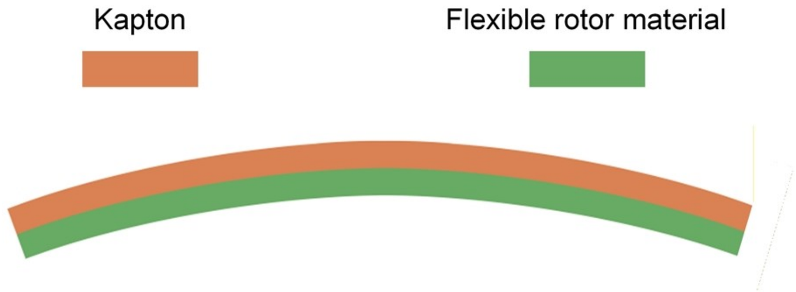
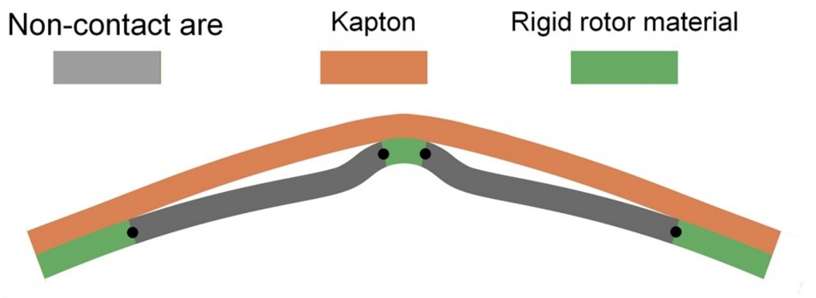


Figure S2. Voltage Frequency, Transferred Charge, and Current of RSCS-TENG under Variable Wind Speeds



(a) Flexible contact



(b) Rigid contact

Figure S3. Schematic illustration of soft and rigid contact

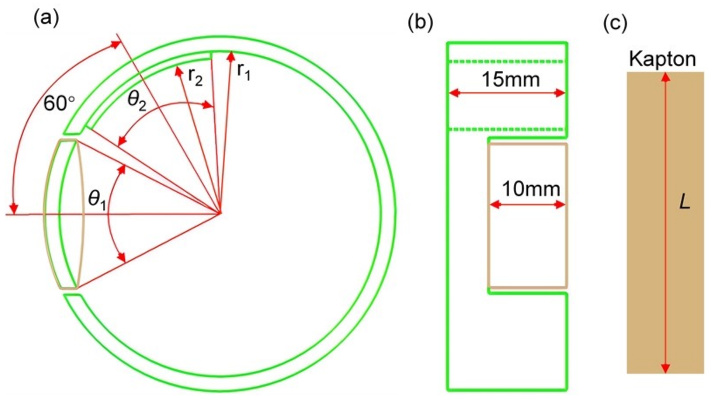
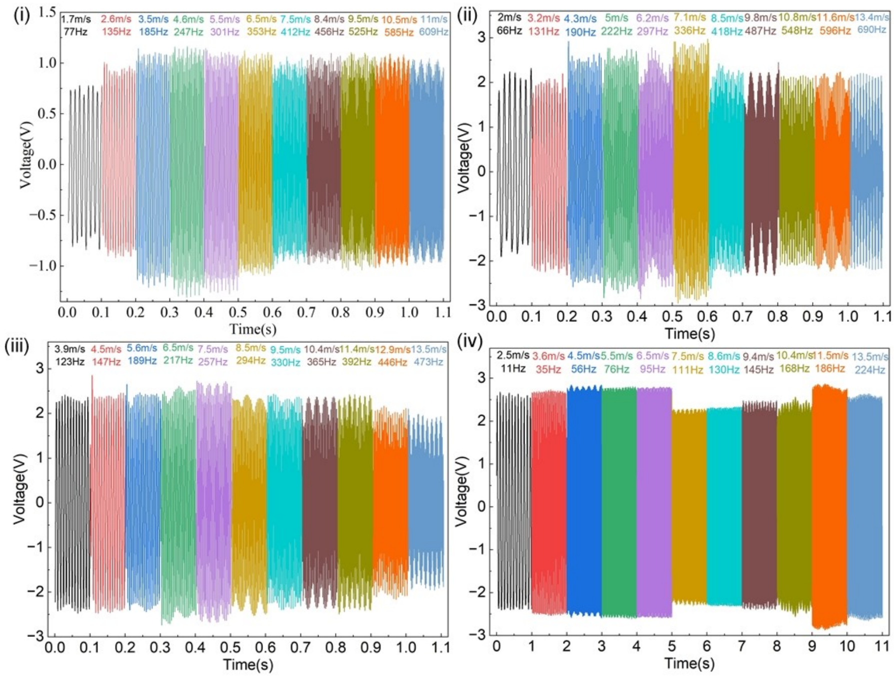


Figure S4. Basic dimensions of stator. (a) Radial basic dimensions. (b) Axial basic dimensions. (c) Kapton length

Table S2.Basic dimensional data for stators with different rotation radii

	θ_1/°	θ_2/°	r_1/mm	r_2/mm	L/ mm
R_1=18.75mm	36.4°	60°	20	19.25	42.5
R_2=13.75mm	43°	60°	15	14.25	36.5
R_3=8.75mm	51.7°	60°	10	9.25	30.5
R_4=5.5mm	63.2°	40°	6.75	6	27



FigureS5. Voltage characteristics of RSCS-TENG at different wind speeds. (i) Voltage characteristics of RSCS-TENG at different wind speeds when the rotation radius is R_4. (ii) Voltage characteristics of RSCS-TENG at different wind speeds for a rotation radius of R_3. (iii) Voltage characteristics of RSCS-TENG at different wind speeds for a rotation radius of R_2. (iv) Voltage characteristics of RSCS-TENG at different wind speeds when the rotation radius is R_1.

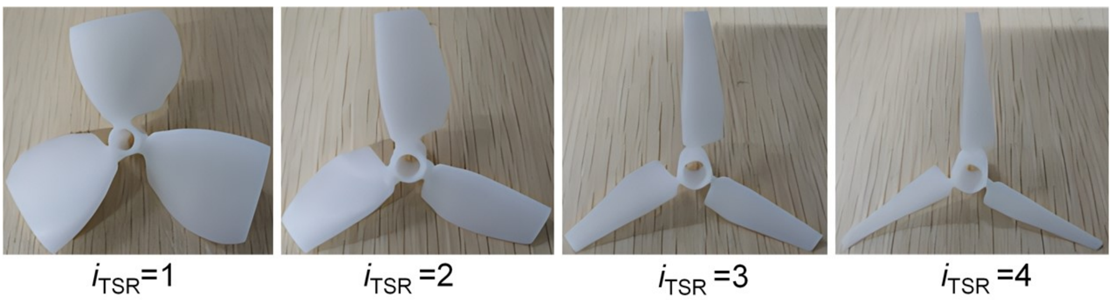
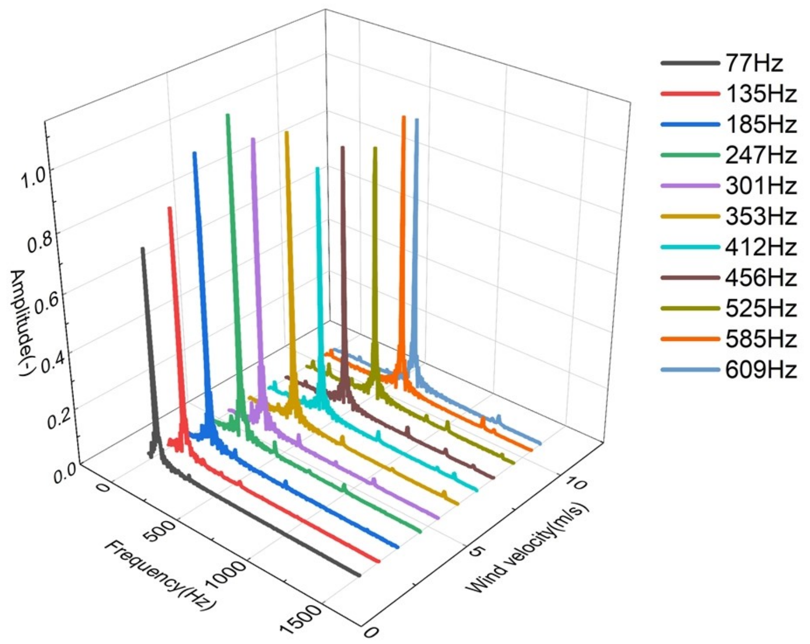


Figure S6. Impeller with different tip speed ratios



FigureS7. RSCS-TENG voltage amplitude-frequency curve at R_4

(i) Blower; (ii) Humidifier; (iii) Heating lamp; (iv) Foam insulation box; (v) Teng wind speed sensor;(vi) Illuminance sensor ;(vii) Temperature and humidity sensor

FigureS8. Temperature, humidity, light intensity environment construction

Table S3. Performance Parameters of Smart sensor AS8556

Smart sensor AS8556						
Wind speed range	Resolution	Operating Voltage	Operating Current	Temperature range	Humidity range	Measurement Accuracy

0.3m/s~45 m/s	0.001m/s	9v	≤20mA	0~50°	≤80%RH	±2.5%±0.1

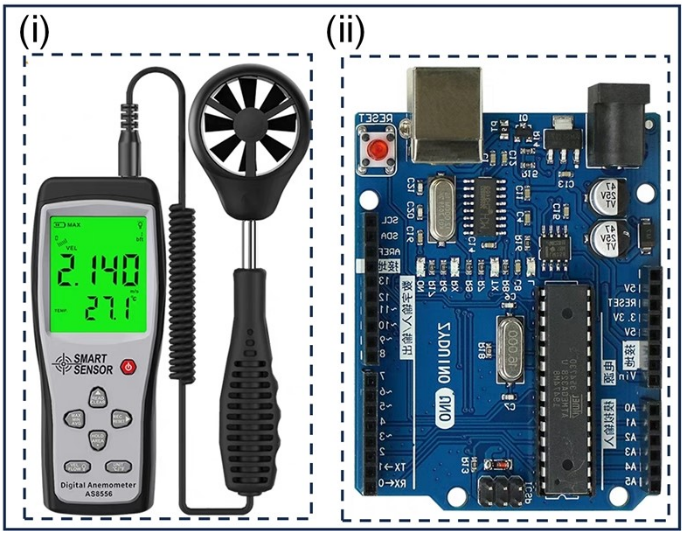
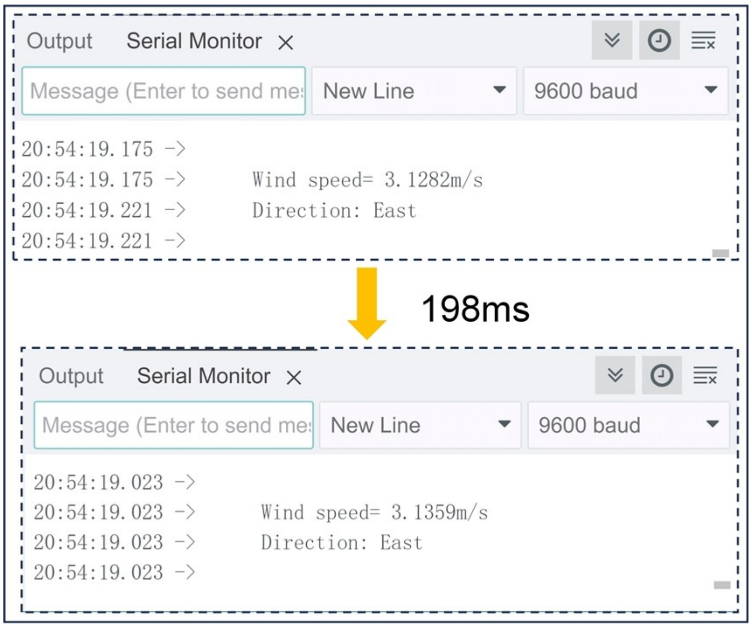
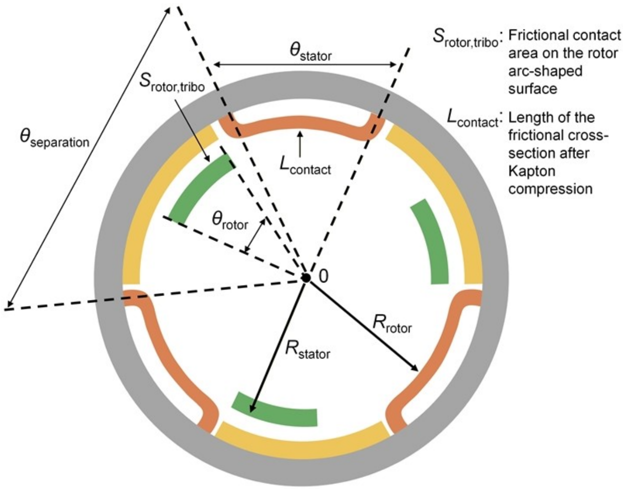


Figure S9. (i) Smart sensor AS8556. (ii) Arduino uno

FigureS10. RSCS-TENG and WD-TENG Sensors



FigureS11. Dynamic Response of Wind Vector Sensing System



FigureS12.The critical dimensions for the rotational soft-contact-separation mode

The total tribological area swept by the rotor per revolution (FigureS12) is calculated as:

$$S_{\mathrm{one,1}} = n_1 n_2 S_{\mathrm{rotor,\ tribo}} L_{\mathrm{contact}} \tag{1}$$

where $n_1 = 3$ denotes the number of rotor frictional materials, $n_2 = 3$ represents the number of stator frictional materials, $S_{\mathrm{rotor,\ tribo}}$ signifies the frictional contact area on the rotor arc-shaped surface, and L_{contact} denotes the cross-sectional length of the stator frictional area.

The cross-sectional length of the stator friction area is expressed as follows:

$$L_{\mathrm{contact}} = 2\pi R_{\mathrm{stator}} \frac{\theta_{\mathrm{stator}}}{360^{\circ}} \tag{2}$$

where R_{stator} and θ_{stator} denote the circumferential radius and angle of the compressed stator frictional material, respectively.

During the contact friction process, the rotor and stator frictional materials are nearly conformal, meaning the circumferential radius of the compressed stator friction material and that of the rotor satisfy the following expression:

$$R_{\text{stator}} = R_{\text{rotor}} \tag{3}$$

where R_{rotor} denotes the rotor friction material's circumferential radius.

For the RSCS-TENG to achieve full separation post-contact, the stator frictional material must have an inter-side separation angle no less than the rotor angle. Based on Figure 1, this separation angle is defined by the following equation.

$$\theta_{\text{separation}} = \theta_{\text{rotor}} + \theta_{\text{extra}} \tag{4}$$

where $\theta_{\text{separation}}$ denotes the inter-side separation angle between opposite sides of the stator frictional material, θ_{rotor} represents the circumferential angle of the rotor frictional material, and θ_{extra} is defined as the additional angle given by $\theta_{\text{separation}} - \theta_{\text{rotor}}$.

When the separation angle between opposite sides of the stator frictional material is $\theta_{\text{separation}}$, the accumulated tribological area per revolution of the RSCS-TENG is given by:

$$\begin{aligned} S_{\text{one,1}} &= n_1 n_2 S_{\text{rotor,tribo}} L_{\text{contact}} = 9S_{\text{rotor,tribo}} \cdot 2\pi R_{\text{stator}} \frac{\theta_{\text{stator}}}{360^{\circ}} = 9S_{\text{rotor,tribo}} \cdot 2\pi R_{\text{stator}} \frac{(360^{\circ} - 3\theta_{\text{separation}})/3}{360^{\circ}} \\ &= 9S_{\text{rotor,tribo}} \cdot 2\pi R_{\text{stator}} \frac{(120^{\circ} - \theta_{\text{separation}})}{360^{\circ}} = 9S_{\text{rotor,tribo}} \cdot 2\pi R_{\text{stator}} \left(\frac{1}{3} - \frac{\theta_{\text{rotor}} + \theta_{\text{extra}}}{360^{\circ}}\right) \\ &= 6\pi S_{\text{rotor,tribo}} R_{\text{rotor}} - \pi S_{\text{rotor,tribo}} R_{\text{rotor}} \frac{\theta_{\text{rotor}} + \theta_{\text{extra}}}{20^{\circ}} \end{aligned} \tag{5}$$

Similarly, for the continuous contact mode under identical basic dimensions, the accumulated tribological area per revolution is given by the following formula:

$$S_{\text{one,2}} = n_1 \cdot S_{\text{rotor, tribo}} \cdot 2\pi R_{\text{rotor}} = 6\pi S_{\text{rotor, tribo}} R_{\text{rotor}} \tag{6}$$

Under the same wind speed, the energy harvested by the impeller is expressed as follows:

$$E = Pt \tag{7}$$

where E represents the impeller-captured energy, P the output power, and t the total operating time of the RSCS-TENG.

Given uniform pressure per unit area across the contact surfaces, the frictional energy generated in the RSCS-TENG over time t is given by:

$$E_{\text{all}} = c_1 \cdot E_{\text{one}} \tag{8}$$

where c_1 indicates the number of revolutions completed by the rotor within time *t,* and E_{one} signifies the single-cycle frictional energy of the triboelectric interface.

According to the per-cycle contact area of the RSCS-TENG, E_{one} is given by the following equation:

$$E_{\text{one}} = \mu.p.S_{\text{one,l}} = \mu.p.(6\pi S_{\text{rotor,tribo}} R_{\text{rotor}} - \pi S_{\text{rotor,tribo}} R_{\text{rotor}} \frac{\theta_{\text{rotor}} + \theta_{\text{extra}}}{20^{\circ}}) \tag{9}$$

where p denotes the interfacial pressure per unit area, and μ indicates the coefficient of friction.

Combining equations (8) and (9), E_{all} is expressed as follows:

$$E_{\text{all}} = c_1.\mu.p.(6\pi S_{\text{rotor,tribo}} R_{\text{rotor}} - \pi S_{\text{rotor,tribo}} R_{\text{rotor}} \frac{\theta_{\text{rotor}} + \theta_{\text{extra}}}{20^{\circ}}) \tag{10}$$

Under ideal conditions, the wind energy captured by the RSCS-TENG is fully converted into triboelectric energy.

$$E = E_{\text{all}} \tag{11}$$

Under identical wind speed conditions, the c_1 of the RSCS-TENG after operating for a duration *t* is expressed as follows:

$$c_1 = \frac{Pt}{\mu.p.(6\pi S_{\text{rotor,tribo}} R_{\text{rotor}} - \pi S_{\text{rotor,tribo}} R_{\text{rotor}} \frac{\theta_{\text{rotor}} + \theta_{\text{extra}}}{20^{\circ}})} \tag{12}$$

Similarly, under continuous friction mode, the number of revolutions c_2 of the rotational anemometer after an operational period *t* is expressed as follows:

$$c_2 = \frac{Pt}{\mu.p.6\pi S_{\text{rotor, tribo}} R_{\text{rotor}}} \tag{13}$$

For identical operational conditions, the rotational speed increase percentage of the soft-contact-separation mode versus the continuous contact mode follows the expression:

$$\lambda = \frac{c_1}{c_2} = \frac{1}{1 - \frac{\theta_{\text{rotor}} + \theta_{\text{extra}}}{120^{\circ}}} \tag{14}$$

Within the soft-contact-separation mode, the following relation holds among θ_{rotor}, θ_{stator}, and θ_{extra}:

$$\theta_{\text{rotor}} + \theta_{\text{extra}} + \theta_{\text{stator}} \approx 120^{\circ} \tag{15}$$

Equation (14) indicates that the speed enhancement ratio λ varies dynamically with θ_{rotor} and θ_{extra}. Combined with Equation (15), the sum $\theta_{\text{rotor}} + \theta_{\text{extra}}$ is constrained to ≤120°, guaranteeing λ ≥

1. Larger relative proportions of θ_{rotor} and θ_{extra} yield increased λ values. By optimizing the weight distribution of θ_{rotor}, θ_{extra}, and θ_{stator}, the rotational soft-contact-separation mode achieves a balance between electrical output and rotational speed, enabling dynamic speed improvement.