Overview of Power Management for Triboelectric Nanogenerators

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Triboelectric nanogenerators (TENGs) have demonstrated enormous potential applications for acquiring human motion energy and ambient mechanical energy, which is the foundation of energy for the new era. However, with alternating current (AC) pulse and huge inherent impedance, the TENGs usually exhibit low-energy supply efficiency when either powering conventional electronics or charging energy storage devices directly. Efficient power management has always been a technical bottleneck for the TENGs toward practical applications in self-powered microsystems. Over the past several years, several strategies of power management have been proposed, such as rectification, electromagnetic transformation, capacitive transformation, and direct current (DC) conversion, which can be used for voltage regulation, impedance matching, and efficiency improvement for electronics. Herein, the recent advances on power management for TENGs are systematically reviewed and analyzed, which has exhibited manageable triboelectric power by electronics as an important research issue of TENGs. Finally, the existing challenges and future perspectives in this field are discussed.

1. Introduction

With the arrival of the fourth industrial revolution, that is based on the internet of things (IoTs), wireless sensor networks (WSNs), and artificial intelligence (AI), the desire for numerous, miniature, and distributed wireless power sources is unprecedented.[1,2] Over the past decades, with huge efforts, several promising new energy technologies based on the effect of the photovoltaic,[3–6] thermoelectric,[7–11] piezoelectric,[12–18] and triboelectric[19–26] have been invented to meet this urgent demand. Especially, the triboelectric nanogenerators (TENGs), derived from the second term in Maxwell’s displacement current and invented by Wang in 2012,[19,27–30] can harvest tiny human kinetic energy[31–35] and ambient mechanical energy,[36–39] which is omnipresent but usually wasted in our daily life. With the advantages of versatile operation modes,[40–43] cost effectiveness,[44] cleanliness,[45] sustainability,[46–48] high efficiency even at low frequency,[49,50] microamplitude,[51] etc., the TENGs have been demonstrated to be the foundation of energy for the new era.[51]

However, for its irregular and random high voltage and low-current pulse output characteristics, the TENGs usually exhibit low-energy supply efficiency when directly either powering conventional electronics or charging energy storage devices,[52,53] which have always been the bottleneck for TENGs toward practical application in self-powered microsystems. Hence, effective power management is highly desired for increasing the energy supply efficiency of TENGs. Over the past years, several strategies of power management have been proposed, such as rectification,[54–56] electromagnetic transformation,[57–59] capacitive transformation,[60,61] and direct current (DC) conversion,[62–64] which can be used for voltage regulation, impedance matching, and efficiency improvement for conventional electronics.

Here in this Review, the electrical model of TENGs was analyzed concisely, and there was a comparison between TENGs, piezoelectric generators (PEGs), and electromagnetic generators (EMGs). Then, the recent advances on power management for TENGs are systematically reviewed and analyzed, which has exhibited manageable triboelectric power by electronics as an important research issue of TENGs. Finally, the existing challenges and future perspectives in this field are discussed.

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2. Fundamentals of TENGs

2.1. Theoretical Source and Equivalent Model of TENGs

In 2012, the TENGs (Figure 1a) were invented,[19] which can generate continuous alternating current (AC) output with the cycle of pressing and releasing between two thin frictional elements. According to previous works,[65,66] the theoretical origin of TENGs is the Maxwell’s displacement current that is defined as

\[ J_d = \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t} + \frac{\partial P_s}{\partial t} \]  

(1)

where \( J_d \) is displacement current, \( D \) is displacement field, \( \varepsilon \) is permittivity of the medium, \( E \) is electric field, and \( P_s \) is polarization contributed by the presence of surface polarization charges induced from triboelectrification. Here, the first term is the basis of electromagnetic waves, and the second term is the origin of nanogenerators (PEGs and TENGs). As shown in Figure 1b, the TENGs consist of two electrodes used to connect with back-end load and two dielectric layers for contact electrification. Due to contact electrification, the surface of two dielectrics possesses opposite charge, which creates an electrostatic field that forces the free electrons to transfer between the two electrodes through the external load. The oppositely charged surfaces with the changing gap distance (\( z \)) can be regarded as a parallel-plate capacitor with variable capacitance (Figure 1c); thus, the TENGs are equivalent to a variable capacitor that connects with a high voltage source in series.[67] The governing equation for TENGs can be written as[68]

\[ V = - \frac{1}{C(z)} Q + V_{OC}(z) \]  

(2)

where \( V \), \( C \), \( Q \), and \( V_{OC} \) represent the output voltage, capacitance, transferred charges, and open-circuit voltage, respectively. Apparently, \( V \) is a function of \( z \), and therefore, mechanical energy that causes a change in \( z \) is converted to electrical energy.

When the TENGs were powered for a resistive load \( R \), the equivalent circuit diagram is shown in Figure 1d(i).[69] Based on the Kirchhoff’s law, the governing equation can be represented as

\[ R \frac{dQ}{dt} = -\frac{1}{C} Q + V_{OC} \]  

(3)

With varying load resistance, the peak values of the voltage, current, and power are shown in Figure 1d(ii),(iii). Obviously, there are three conditions corresponding to the three regions in Figure 1d-ii. In region I, the resistance is low (<1 \( \Omega \)), the peak current has little drop compared with the short-circuit condition, whereas the peak voltage is nearly proportional to the loading resistance. In region II, with a medium resistance (1 \( \Omega < R < 1 \text{G} \Omega \)), the peak current decreases rapidly and the peak voltage exhibits a contrary tendency. In the last region, where the resistance is larger than 1 \( \text{G} \Omega \), the output characteristics are close to the open-circuit condition, i.e., the peak voltage saturates at \( V_{OC} \) while the current approaches zero.[69]

When TENGs were used to supply for capacitive load, the equivalent circuit is shown in Figure 1e(i).[53] Based on Kirchhoff’s law and node charge conservation, the following equation can be obtained

\[ V = -\frac{Q}{C_T} + V_{OC} = \frac{1}{C_L} Q_C \]  

(4)

Only when \( C_L \) is equal to \( C_T \), under the state of impedance matching, the energy stored in \( C_L \) reaches its maximum (Figure 1e-iii).

From the aforementioned analyses, we can conclude that TENGs exhibit high output impedance due to the inherent capacitance. And thus, it exhibits low-energy supply efficiency when directly either powering general electronics or charging energy storage devices with low impedance. Efficient power management is the key to the practical application of TENGs as an ideal power source.

2.2. Comparison of TENGs, PEG, and EMG

Following EMG and PEG, TENGs have been widely demonstrated as another major technique for capturing mechanical energy. Chunlong Fang received his B.S. degree in material chemistry from the Shaanxi Normal University in 2017. Currently, he is pursuing his master’s degree under the supervision of Professor Chi Zhang at the University of Chinese Academy of Sciences. His research interests are mainly focused on tribotronics and self-powered microactuators.

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energy and converting it into electrical energy. To reveal the unique strengths and characteristics of TENGs, a comparison among TENGs, EMG, and PEG is necessary.

According to the reported work,[70,71] the EMG with resistance and inductance impedance characteristics, that means low internal impedance, while PEG and TENGs usually exhibit high internal impedance due to the capacitance impedance characteristics. In other words, the EMG usually produces a high short-circuit current ($I_{sc}$) and a low open-circuit voltage ($V_{oc}$), whereas the TENGs could generate a high $V_{oc}$ and a low $I_{sc}$, as shown in Table 1.

And thus, as a power supply for conventional electronics or energy storage devices, power management is essential. For the traditional generator, EMG, the power management has been very mature, which can meet the needs of power generation, transformation, and transmission. Similarly, for PEG, after rapid technology accumulation for years, there are several commercial power management modules (PMMs) for PEG, such as LTC3588. However, as an emerging energy technology, there is no commercial PMM for TENGs at present.

Table 1. A comparison of EMG, PEG, and TENGs in internal impedance, impedance characteristics open-circuit voltage, and short-circuit current.

|                | EMG       | PEG       | TENGs   |
|----------------|-----------|-----------|---------|
| Internal impedance | $\Omega$  | $\Omega$  | $\Omega$ |
| Impedance characteristics | Resistance, Inductance | Capacitance | Capacitance |
| Open-circuit voltage | Low       | Medium    | High    |
| Short-circuit current | High      | Medium    | Low     |
3. Rectification for TENGs

3.1. Full-Wave Rectification

Full-wave rectification is regarded as an effective approach to convert AC to DC. In the early years, many researchers applied this method to manage the output of TENGs.[54–56,72] As shown in Figure 2a,c, Wang[55] and Su[54] successfully proposed the self-charging unit and self-powered microsystems based on this strategy. From Figure 2b,d, it is obvious that the output current and voltage of TENGs were converted into pulsed DC from pulsed AC.

But, as the impedance between TENGs and the rectifier bridge does not match, plenty of energy is lost during the rectification process. Therefore, the strategy of full-wave rectification still does not break the bottleneck of low-energy supply efficiency when TENGs are used as power supply for conventional electronics.

3.2. Half-Wave Rectification

Xu et al.,[73] by applying the half-wave rectification method, introduced a triboelectric charge supplement channel in the TENGs, the schematic diagram is shown in Figure 3a. Different from the common half-wave rectification, the power source, diode, and load are in parallel in this management strategy. In the negative
half period, the charges could transfer from one electrode to another, replenishing the dissipated charges, keeping throughout the TENGs electrodes under an optimal charge distribution, and obtained a much higher DC open-circuit voltage under the given surface charge density and device configuration. As shown in Figure 3b, the open-circuit voltage is significantly boosted from $\approx 230$ V to more than 3300 V, and it is over ten times. More importantly, this method effectively addressed the problem of discreteness on the TENG open-circuit voltage (see Figure 3b inset).

Based on this power management strategy, the TENGs could provide a reliable high voltage supply, that can be used in high-voltage instruments, actuators, and many other fields.

3.3. Bennet’s Doubler Voltage Rectification

Based on the principles of Bennet’s doubler device, Ghaffarinejad et al. provided another efficient power management method for TENGs. The equivalent circuit diagram is shown in Figure 4a, and it only consists of few diodes and capacitors, embodying the advantages of simplicity. As shown in Figure 4b, within one of the TENGs operation cycles, the connection state of the capacitors in series or parallel changes by switching the state of the diodes (on or off). The compared result is shown in Figure 4c,d; the reservoir capacitance $C_{res}$ could be charged to 165 and 26 V, respectively, when using the half-wave rectifier and full-wave rectifier management circuit, and to 835 V when using Bennet’s doubler management circuit (Figure 4c).

Figure 4d shows that the energy stored in $C_{res}$ increases in exponential, whereas the energy stored by half-wave or full-wave rectification increases first and then decreases at a very low value. And thus after 140 s, the energy stored in $C_{res}$ based on Bennet’s doubler voltage rectification is much more than that based on half-wave or full-wave rectification.

Based on this power management strategy, the energy stored in $C_{res}$ shows an exponential increase, once the ratio of the largest capacitance to the smallest capacitance of TENGs is larger than 2. Therefore, the problem of TENGs’ charging inefficiency is alleviated to some extent.

4. Electromagnetic Transformer for TENGs

Electromagnetic transformation is a common strategy for the lowering voltage and rising current, which is also applied to manage the output of TENGs. Initially, researchers directly introduced an electromagnetic transformer between TENGs and external load as shown in Figure 5a. The dependence of output performance of the TENGs without/with an electromagnetic transformer on the external loading resistance is shown in Figure 5b,c. After comparison, we can find that the output impedance was reduced significantly, at 2 KΩ load (this is much lower than the internal output impedance of TENGs), and the peak output power reached 1.4 mW. To some extent, the output of TENGs has been managed, impedance reduced, and power supply efficiency improved. However, for the time-dependent output attribute, it still does not work as a real power source for microsystems.

Zhu et al. designed a power management strategy based on the electromagnetic transformer. As shown in Figure 5e, it consists of a rectifier, capacitors, a regulator, and an electromagnetic transformer. Based on this power management strategy, the output of the TENGs is modulated into 5 V DC output in 0.5 s after the TENGs begin to work at 3000 r min$^{-1}$ (Figure 5f). Obviously, it is an important progress on the power management of TENGs.

As is well known, the coil turns ratio is one of the key factors that determines the performance of the electromagnetic transformer. Based on this, Pu et al. studied the effects of coil ratio on TENGs output management, as shown in Figure 5g–i. As the coil ratio increased from 1 to 36.7, the current increased from 2.0 to 73.5 mA, whereas the voltage decreased from 391.4 to 9 V. At the same time, the power utilization efficiency significantly improved from 1.2% to about 72.4% (Figure 5i).

From the aforementioned, we can understand that the power management strategy based on the electromagnetic transformer is an effective method for TENGs, which improved the energy supply efficiency, but this required operation in a high frequency (more suitable for Rotary-TENGs, as shown in Figure 5d),
and the customized transformer is larger in size. These mal-practices still restrict TENGs as power source conventional electronics.

5. Capacitive Transformers for TENGs

Unlike the power management strategy based on electromagnetic transformer prefer to TENGs operation at a high frequency, the power management circuit based on capacitive transformer has no requirement on the working frequency of TENGs.

Tang et al.\(^6\) designed a novelty TENG, as shown in Figure 6a, a power-transformed-and-managed TENG (PTM-TENG), which contains a contact-separation mode TENG and a set of capacitors that are in series during charge and in parallel during discharge. The detailed working process is shown in Figure 6b. Based on the principle of the capacitor transformer, for TENGs, the voltage can be tunably decreased whereas the current and charges can be increased. The output charges and voltage can be represented as follows

\[
Q_{\text{out}} = NQ_0
\]  
(5)

\[
V_{\text{out}} = \frac{V_0}{N}
\]  
(6)

where \(V_0\) and \(Q_0\) are the total storage voltage and charges in the serial capacitors and \(N\) is the number of capacitors. The experimental results (Figure 6c,d) are in agreement with the theoretical analysis very well, which means that the output voltage is reduced \(N\) times whereas the output charges is enhanced \(N\) times. Also, the power supply efficiency is significantly improved when charging a 10 \(\mu\)F commercial capacitor, as shown in Figure 6e.

Zi et al.\(^6\) optimized and applied this power management strategy on a lateral-sliding (L-S) mode TENG, as shown in Figure 6f, achieving a higher charging speed for the super-capacitor, and the maximum efficiency reaches 25% (Figure 6g).

However, because of the complex mechanical layout, the number of the switch is limited, which means the effect of power management is limited.
6. DC Buck Conversion for TENGs

6.1. \( V-Q \) Plot of TENGs

As research, Zi et al.\(^7\) demonstrated that the output of TENGs can be described by the following parameters: the amount of charge transferred between electrodes (\( Q \)), the voltage between electrodes (\( V \)), and the relative displacement between friction layers (\( x \)). The generated energy in per operation cycle, \( E \), can be expressed as the enclosed region in the \( V-Q \) curve as the following equation:

\[
E = \bar{P}T = \int_0^T VdI dt = \int_{t=0}^{t=T} VdQ = \oint VdQ
\]

\( (7) \)

Figure 5. Electromagnetic transformer for TENGs. a) Electrical circuit diagram and b,c) without/with power management. Reproduced with permission.\(^{[57]}\) Copyright 2015, American Chemical Society. d) Schematic illustrations of the radial arrayed rotary TENGs; e) Electrical circuit diagram and f) the output performance of TENGs after management. Reproduced with permission.\(^{[58]}\) Copyright 2014, Springer Nature. g) The electrical circuit diagram; h,i) The management performance with different coil ratio of transformer. Reproduced with permission.\(^{[59]}\) Copyright 2016, Wiley VCH.
The researchers take an L–S mode TENG as an example, as shown in Figure 7a. The V–Q curve starts to overlap after a certain number of cycles, as plotted in Figure 7b. Also, the new cycle of maximum energy output (CMEO) is proposed based on instantaneous short-circuit conditions during TENGs operation so that \( Q_c \) reaches peak value (Figure 7c). At steps 1 and 3, the relative displacement between two friction layers varies from \( x = 0 \) to \( x = x_{\text{max}} \), and TENG power for the external load resistance. While at steps 2 and 4, the switch is turned on, and the external load is in short circuit so that the transferred charges \( Q \) reach \( Q_{\text{SC,max}} \) and 0, respectively. Also, the CMEOs under a set of load resistances are shown in Figure 7d, it indicates that the maximized energy output per operation cycle \( (E_{\text{max}}) \) could be achieved when \( R \) tends to infinity.

Xu et al. \cite{79} introduced the oscillating circuit to realize the flip of charge polarity on the conductive layer, the detailed working mechanism is shown in Figure 7e. When achieving the peak voltage of TENGs and closing the switch and the charge in the conductive layer reversed by the oscillating circuit, the voltage is also reversed, and then the switch is turned off. The reversed free charges on the conductive layer will not neutralize the polarized charge but increase the amount of equivalent charge, as.
Figure 7. V–Q plot of TENGs. a) Schematic diagram of the L–S mode TENG. b) The cycles for energy output (CEO) with load resistance $R = 100 \, \text{M}\Omega$. c) The CMEO with load resistance $R = 100 \, \text{M}\Omega$. d) The CMEO with various load resistances. Reproduced with permission.[78] Copyright 2015, Springer Nature. e) The operation cycles for oscillation assisting TENGs. f) The charge distribution of oscillation-assisting TENGs. g) The V–Q curve for the oscillation-assisting TENGs. Reproduced with permission.[79] Copyright 2018, Wiley-VCH.
shown in Figure 7f. Due to the phase difference between voltage and current, the reactive power should be considered. And hence, the energy output of TENGs is not only the enclosed area of the $V$–$Q$ curves, but also the coverage area of the $V$–$Q$ curve and the $Q_{axis}$, as shown in Figure 7g. It means that more energy is extracted from the environment.

The $V$–$Q$ theory provides theoretical guidance for power management; based on this, one can maximize energy output per cycle of TENGs. It should be noticed that the switch plays an indispensable role in $V$–$Q$ theory.

6.2. DC Buck Conversion with Mechanical Switch

6.2.1. Travel Switch

Cheng et al.\cite{100} developed instantaneous discharging TENGs based on the travel switch, the schematic diagram and operation mechanism are shown in Figure 8a,b. It can convert the output of TENGs into instantaneous discharging from continuous discharging. The detailed comparison of output performance is shown in Figure 8c. From this comparison, we can see that the output is significantly enhanced at a relatively smaller resistance based on this management. The instantaneously maximum current density reached 1325 A m$^{-2}$; this is more than 2500 times higher than the continuous discharging TENGs.

With the assistance of the $V$–$Q$ theory of TENGs, Zi et al.\cite{101} proposed a power management strategy based on travel switch, and the equivalent circuit diagram is shown in Figure 8d. The authors initially obtained the maximized output energy based on the $V$–$Q$ plot using a mechanical switch and designed the charging cycle. Then, the output energy is stored in a capacitor. Finally, with the assistance of a power converter and a divider resistor, a commercial calculator was powered successfully without any other power supply. As validated in Figure 8e, this proposed power management is applied for TENGs, and the output energy of per cycle after management is significantly higher than that before management.

Huai et al.\cite{102} proposed another power management strategy based on the travel switch. Similarly, it is based on the $V$–$Q$ plot’s maximized energy output with the aid of the travel switch. The difference is that the output energy is stored in an inductor and then transferred to the external load. The detailed operation process is shown in Figure 8f. With this proposed strategy, after 145 s, the stored energy in a commercial capacitor reaches 470.73 μJ, which has nearly 12 times improvement over that without this power management, and the maximum energy supply efficiency reaches 48.0% (see Figure 8g).

Based on the aforementioned discussion, we can get with the proposed management strategies, and the bottleneck issue for TENGs as a power supply for conventional electronics has been alleviated. However, for the TENGs travel switch, a special structural design is required, which greatly reduces the universality of TENGs.

6.2.2. High-Voltage-Triggered Switch

Apart from the travel switch, another mechanical switch was applied to manage triboelectricity, which is triggered by the output voltage of TENGs.

Cheng et al.\cite{103} designed a self-triggered discharge strategy for the management of triboelectricity, as shown in Figure 9a, and it consists of a tungsten tip electrode and a stainless steel plate electrode. The working mechanism is only when the output voltage exceeds the threshold voltage of inducing air discharge, the switch is triggered and output electricity. And thus, the output of TENGs is converted into instantaneous from continuous. The experimental results (Figure 9b,c) show that the output peak power and total energy are significantly enhanced on a relatively small resistance, which means the output impedance is significantly reduced successfully.

Yang et al.\cite{104} designed an electrostatic vibrating switch for the management of triboelectricity, as shown in Figure 9d. The operation principle is, during the operation process, the voltage of the TENGs is used to drive the vibration of the vibrating switch; thereby, the periodic electrical output is generated when the switch is triggered and thus, maximizing the energy output per cycle for TENGs. The experimental results indicated that the output peak power and total energy are significantly enhanced on a relatively small resistance, which means the output impedance is significantly reduced.

As analyzed earlier, applying the high-voltage-controlled switch can manage the output of TENGs effectively. However, it is clearly not consistent with the TENGs universality; due to this strategy, it is more suitable for TENGs with a high output performance.

6.3. DC Buck Conversion with Electronic Switch

6.3.1. Electronic Switch with Back-End Power Supply

Due to the drawbacks of mechanical switches in power management, researchers paid great efforts to replace them with electronic switches.

Niu et al.\cite{105} proposed an efficient power management strategy for TENGs, which is based on electronic switches controlled by a logic circuit. The equivalent circuit diagram is shown in Figure 10a. The management mechanism is as follows.

First, a small temporary capacitor ($C_{temp}$) is charged by the TENGs until its voltage reaches $V_{opt}$, then the $C_{temp}$ begins to transfer energy to the final energy storage unit. When the energy transfers are finished, the voltage of $C_{temp}$ drops back close to 0, and $C_{temp}$ is recharged by the TENGs to reach $V_{opt}$ again. The switching of the above two states is controlled by the electronic switches ($J_1$ and $J_2$), which is controlled by the logic circuit. Notably, the transfer efficiency reaches 60% from AC energy to DC electricity.

Zhang et al.\cite{106,107} developed a similar power management strategy based on the $V$–$Q$ theory used as the electronic switch controlled by logic circuit. The equivalent circuit diagram is shown in Figure 10c.f. After management, the output impedance of TENGs was significantly reduced, and the energy storage efficiency enhanced 2600 times than before for charging a 4.7 mF capacitor, as shown in Figure 10d.e. Based on this, a high-efficiency self-powered smart bracelet was invented by integrating TENGs, PMM, and micro-super-capacitors, with the aid of flexible PCB technology. By simultaneously converting and storing the body motion energy, a temperature–humidity meter and pedometer were powered successfully.
The proposed electronic switch has advantages of reliability and stability over mechanical switch and exhibited a well-deserved power management effect. However, the proposed power management strategy requires the whole management system always in the state of having prestored power. Apparently, it is not suitable for the condition of a long standby mode.
due to the large leakage in the whole system. Once the prestored power is exhausted, the power management circuit cannot work anymore. Therefore, developing a power management strategy that does not require any prestored power is highly desired.

6.3.2. Electronic Switch with Front-End Power Supply

**Autonomous Buck Conversion:** Zhang et al.\cite{62,88} proposed a universal, efficient, and autonomous power management strategy which is based on the maximization energy transfer, DC buck conversion, and self-management mechanism. As shown in Figure 11, this work operation mechanism is as follows.

The first is to maximize the transfer of energy from the TENGs to the back-end circuit, which is based on the $V$–$Q$ theory, as shown in Figure 11a. The switch consists of a metal–oxide–semiconductor field-effect transistor (MOSFET) and comparator, and the reference voltage of the comparator is based on the peak output voltage of TENGs. Once the output voltage of TENGs reaches its peak, the comparator will send a high voltage to turn on the MOSFET. When the energy of the TENGs is completely released, the switch turns off automatically. On this basis, a tri-biobotic energy extractor (TEE) based on an autonomous switch and rectifier is proposed, which can maximally extract energy and transmit it to the back-end circuit automatically (Figure 11c). Also, the maximum energy extraction efficiency reaches 84.6\% (Figure 11d,e).

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**Figure 9.** High-voltage-triggered switch for TENGs. a) The schematic diagram of the voltage-triggered discharge switch integrated with TENGs. b) Output peak power and c) output energy per cycle on load resistances. Reproduced with permission.\cite{83} Copyright 2018, Elsevier. d) The schematic diagram of voltage-triggered vibrator switch integrated with TENGs. e) Output peak power and f) total output energy on various resistances. Reproduced with permission.\cite{84} Copyright 2018, Elsevier.
After achieving energy maximization transfer autonomously, the output of TENGs is still a time-dependent pulse high voltage. Apparently, it is not suitable to power conventional electronics directly. And hence, a classical DC–DC buck converter is integrated to convert the output into a low-voltage DC signal (Figure 11b(i)). When the switch is closed, TENGs give the power to load while the inductor and capacitor store energy (Figure 11b(ii)); when the switch is turned on, the circuit continues to flow through the diode, and the inductor and capacitor supply the load (Figure 11b(iii)). Based on the proposed management strategy, with 1 Hz mechanical stimuli, the matched impedance of the TENGs is converted to 1 MΩ from 35 MΩ with 80% efficiency, and the power supply efficiency is improved 128 times when charging a 1 mF commercial capacitor (Figure 11f).

Notably, in this management strategy, the TENGs are used to supply power for the electronic switch to manage triboelectricity, achieving direct front-end power supply while without any
prestored power and thus realizing real-time autonomous power management with a high efficiency for the TENGs. Based on the exciting management effects, this work has demonstrated that TENGs with PMM can offer a complete microenergy solution for wearable electronics,

Figure 11. DC buck conversion with front-end power supply E-switch. a) The enlarged encircled area for CMEO using a sequential switch. b) Schematic circuit diagram of AC–DC buck conversion. c) The schematic circuit diagram of the TEE. d) The voltage and transferred charges of the TENGs with the TEE. e) The V–Q plot of the TEE with about 85% efficiency. f) A comparison of direct and managed charging for a 1 mF capacitance. g) PMM-based self-powered microsystems based on human kinetic energy harvesting. Reproduced with permission. Copyright 2017, Elsevier. h) PMM-based self-powered microsystems based on environmental mechanical energy harvesting. Reproduced with permission. Copyright 2019, Wiley-VCH.
Autonomous Voltage Regulation: After the output energy maximization and DC buck conversation, the output of TENGs was modulated into DC with a low voltage. However, for the time-dependent properties of TENGs energy harvesting, the voltage after DC buck conversation is still not steady, which means it still does not satisfy the operating voltage requirement of sensors, controllers, transmitters, and other conventional electronics, a constant and steady DC voltage is indispensable. Therefore, voltage regulation is necessary before powering conventional electronics.

Zhang et al.\cite{63} obtained a great process on power management for TENGs based on previous work, that achieved a steady DC low voltage. The circuit schematic diagram is shown in Figure 12a, and it consists of a buck convertor, a capacitor, and a regulator. The function of the buck convertor is achieving impedance and voltage conversion of the TENGs, and its operation process is discussed in the last section; the difference is that the energy transferred to the $L-C_1$ unit eventually is stored in $C_2$ and then connected with a voltage regulator circuit; the stored voltage $V_S$ is adjusted by switching the state of the switch ($S_2$). It is noteworthy that the $S_2$ used for voltage regulation is also directly powered by triboelectricity, without any external power supply.

Based on the proposed management strategy, the time-dependent and irregular pulse high voltage of the TENGs has been modulated into a steady and continuous DC low voltage (Figure 12b), which can be directly used to power various back-end electronics, such as microprogrammed control units, microelectromechanical system sensors, and a wireless transmitter. Also, a self-powered intelligent microsystem is successfully built, which can harvest energy, sense information, and transmit data (Figure 12c). By continuously harvesting the wave energy, the proposed self-powered intelligent microsystems can provide the measurement data through wireless communication to maintain the flow in a steady stream without any external power supply, which indicates that the TENGs integrated with PMM can thoroughly replace the traditional power supply for microsystems (Figure 12d). Moreover, for powering the microcomputer.

Figure 12. Voltage regulation with a front-end power supply E-switch. a) The circuit schematic diagram of the PMM. b) The stored and regulated voltage waveforms. c) Schematic map of the intelligent monitoring mechanism for energy deployment, information sensing, and data transmission. d) Applications of the intelligent monitoring microsystems. Reproduced with permission.\cite{63} Copyright 2019, Wiley-VCH.
and sensors, it satisfies the requirements for machine learning, which is expected to advance toward the self-powered smart ocean based on blue energy.

7. Conclusions

In this Review, the recent advances on power management for TENGs have been summarized and analyzed systematically, which can be classified into four categories—rectification, electromagnetic transformation, capacitive transformation, and DC conversion. Based on these, the output impedance of TENGs is significantly deduced, and thus, the energy supply efficiency is enhanced drastically, exhibiting manageable triboelectric power by electronics as an important research issue of TENGs. The remarkable management effect is defined as power triontronics, which not only breaks through the bottleneck of the low-energy supply efficiency of triboelectricity but also promotes the development of triontronics. More importantly, the output of TENGs can be modulated into a constant DC with a low voltage, which can replace the conventional power source as the energy for the new era to power IoTs, AI, portable electronics, and so on. Despite achieving significant progress on power management for TENGs, as a core research field, many challenges remain to be addressed.

First, the performance of PMM for TENGs is optimized, especially for efficiency, universality, durability, and stability. The current PMM has achieved good performance in a single aspect or several aspects, but considering all aspects, there is still a lot of space to improve before industrialization.

The second challenge involves developing flexible, biocompatible, and disintegratable new PMM. TENGs that have been demonstrated could be used as a promising power supply for wearable electronics and implantable health devices. Thus, addressing the flexibility, biocompatibility, and disintegratability of PMM is highly desired. This needs to start from material selection, processing technology, and other aspects.

Finally, realizing the structural and functional integration including the TENGs, PMM, and back-end functional devices is required. For the PMM, excellent adaptability and universality are required regardless of the working mode and output performance of TENGs. It needs the cross-integration development of electronic, mechanical, and other disciplines.

For the remarkable merits, TENGs have been demonstrated as the foundation energy of the new era. As a bottleneck technology for TENGs practical, power management has broken through the issue of low energy supply efficiency. With the assistance of power management, TENGs not only can act as ideal power sources, replacing batteries for powering conventional electronics, such as watch, calculator, and others, but also meet the desire of numerous, miniature, and distributed wireless power sources of the new area such as, IoTs, AI, big data, and so on.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

energy for the new era, power management, power triontronics, self-powered microsystems, trionetolectric nanogenerators

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