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REVIEW

The potential application of the triboelectric nanogenerator in the new type futuristic power grid intelligent sensing

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Abstract

To meet the requirements of power grid operation control, constructing an extensive sensor network in the power grid is a future development trend. However, due to the high cost, the difficulty of continuous power supply for a long time, the large amount of energy consumption, and the environmental problems caused by abandoned batteries, the traditional power supply mode based on batteries for sensors is inconsistent with China's goal of carbon peak and carbon neutrality. It cannot meet the needs of the future grid. Therefore, it is significant to solve the energy supply problem of numerous sensors to promote the construction of new power grid and improve the utilization rate of renewable energy. As an emerging energy harvesting device, triboelectric nanogenerators (TENG) are suitable for developing self-powered sensors and powering low-power sensors due to their mall size, high efficiency, low cost, and environmental friendliness. At the same time, due to the abundant, stable, and widely distributed magnetic field around the equipment in the grid, it can provide continuous excitation for the TENG. Therefore, applying magnetic field energy-harvesting TENG in the future power grid has a broad development prospect. This paper analyzes the development trend and the crucial problems facing the power grid in the future. We review the research and application of TENG based on the magnetic field in recent years and explain the mechanism of TENG in detail. Finally, the application prospect of TENG in the future power grid has been prospected. This paper can provide a reference for applying magnetic field energy harvesting triboelectric nanogenerators in future power grids.

KEYWORDS

micro/nano-power sources, new power system, self-powered sensors, smart grid, triboelectric nanogenerator

1 | INTRODUCTION

From the beginning of the 21st century, new energy power access grids have become the primary measures for energy consumption as well as environmental pollution which resulted from the high-speed development of society.[1–4] To solve profound changes in a power grid structure and operation characteristics brought about by the progress of large-scale new energy access and transmission technology,[5–7] and realize the transformation to a new power system characterized by safety and efficiency, clean and low-carbon, flexible and intelligent integration, interconnection technologies such as the digital twin and Internet of Things have been widely applied.[8,9] The construction and operation of the new power system require monitoring and analysis of the running state of each node in the power grid, so as to realize the efficient coordination and coordination control of various power sources, power grids, loads, and energy storage in the new power system. However, many nodes need to collect data in the power grid, and many data collection nodes are located in high-cold, high-altitude, and high-humidity areas. The numerous sensors' power consumption and energy supply issues are increasingly prominent. Suppose traditional batteries continue to be used to power these above sensors, in this case, it will not only bring about the issues of massive energy consumption, the need for regular maintenance, difficulty disposing of waste batteries, high cost of low-temperature batteries, but also the charging and discharging capacity as well as the service life of batteries in the cold areas will be significantly reduced.[10–13] This is will inevitable and limits the development of the new power grid to a large extent.

With the low-power electronic devices evolving, the power consumption of sensors has continued to decrease, which has attracted widespread attention from researchers for small-scale energy collection technology.[14–17] Over the past decade, researchers have been actively developing devices that can continuously collect energy from the surroundings to realize self-powered sensor devices.[18–20] To solve the power supply problem of data acquisition sensors and special demand in the power grid, researchers have extensively researched self-powered systems composed of electromagnetic and piezoelectric devices that collect transmission lines' magnetic and vibration energy.[21] However, due to its poor adaptability to low-frequency characteristics, low energy capture efficiency, high cost, difficult maintenance, and sometimes may even affect the transmission line, the application, and development of its energy collection are further limited.[22–24] In 2012, TENG as proposed by Wang and his team was the first to apply the triboelectric effect in the field of energy harvesting by coupling the triboelectric effect with the electrostatic induction effect.[25] Due to its simple structure, low cost, comprehensive source of materials, high energy conversion efficiency, and effective collect stray energy from the surrounding, TENG has broad application potential in the field of self-powered sensors and micro/nano sources.[26] Many studies have found that the emergence of TENG makes it possible to drive sensor devices by collecting the mixed magnetic fields around the transmission line and in the environment.[27–31] TENG has good output performance and can still operate stably under low-temperature conditions,[32] which can solve the energy supply problem of data acquisition sensors in the power grid, and provide a feasible scheme for sensor power supply in special environments, which has a broad application prospect.

This article reviews the current application of TENG in magnetic field use. Firstly, the potential application scenarios of TENG in future power grids were introduced. Then we present the principles and applications of magnetic energy trapping. Finally, the prospect of TENG in magnetic energy trapping and the prospect of future new power systems were discussed.

2 | FUTURE POWER GRID TRANSFORMATION AND POTENTIAL APPLICATIONS OF TENG

2.1 | Future grid transformation direction and needs

The pollution problems caused by the heavy use of fossil fuels have brought broad public concerns worldwide.[33] Although the power industry is the focus of priority development in the economic development strategy of various countries, it is also one of the primary sources of carbon emissions.[34] With the rapid development of human society, the use of electric energy has surged, and the requirements for electricity quality are gradually increasing. At the same time, problems such as decreased operating efficiency of power grid equipment, resource decay, and environmental pollution are also growing. Considering the requirements of ensuring the security of the energy supply, protecting the environment, and improving the economic benefit of the power grid, the research, and application of renewable energy have gradually become the trend of energy policy-making in major countries.[35] Traditional power networks and control measures have proven ineffective to support many development requirements.[5,36] To address these challenges in power system development, new power system networks that utilize new energy sources efficiently and safely and the application of emerging energy harvesting technologies are considered effective solutions, as shown in Figure 1.

To build a new power system with new energy as the main source, a large number of new energy utilization strategies and technologies have emerged and gained widespread attention and flourished. Distributed power generation has attracted widespread attention from people. A large number of new energy power generation and other distributed power generation forms have gradually become connected to the public power grid. Promoted progress of distributed energy resources (DER) and energy storage technology (EST) has reduced the power loss of the transmission and distribution grid. To some extent, it improves the stability and environmental friendliness of the system.[37] At the same time, the advancement of power electronics technology has improved the reliability of power grid construction.[38] Ultra-high voltage direct current (UHVDC) transmission technology also has great advantages in new energy power transmission, giving it excellent development prospects.[39] In order to improve the grid connection rate of DER, Microgrid technology comes into being.[40]

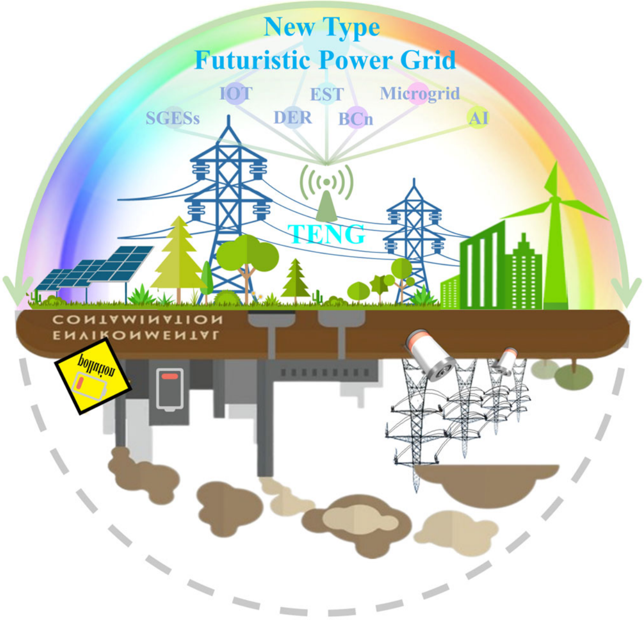

FIGURE 1 Impact of new power grids and energy collection technology on the energy industry.

Furthermore, to reduce the multiple conversions of AC-DC, a hybrid microgrid with the advantages of both AC and DC microgrids is proposed, which will be one of the important development trends of the microgrid in the future. On the other front, smart distribution networks further promote the use of clean energy. It supports the parallel operation of a large number of distributed power sources, energy storage devices, and renewable energy power sources in the distribution network, which provides solid energy storage and power supply capabilities for the grid.[41] In the distribution network security system, the self-healing technology of the smart distribution network is the core technology representative of its security guarantee system. Intelligent early warning and automatic control can accurately identify the type of fault and determine the fault position to achieve control and timely repair of the fault, thus ensuring the normal operation of the power grid.[42] At the same time, due to the great advantages of electric vehicles in energy saving and emission reduction, the encouragement of relevant policies, and the rapid decrease in the cost of pure electric vehicles, their number is snowballing, so the load change of the power system will appear new rules.

With the development and scale of the power system, the demand for data measurement accuracy and convenience is also increasing. Internet of Things (IoT) technology can solve the problem of power system planning and interact with multiple energy management goals. It is foreseeable that the IoT technology will not only gradually develop in support of the power grid but will also further promote the optimization of the power grid to make it modern. Combining the IoT and smart grid will greatly enhance the new power grid's information and communication support capability.[43] The interactivity of the IoT will improve user satisfaction and efficiency and provide consumers with greater rights to communicate and choose, which will help build a more connected, economical, and efficient new power grid.[44]

The technical progress of the smart grid energy system (SGES) and Blockchain (BC) technology is expected to realize functions such as optimizing the energy network, energy transactions, and power grid automation in the future.[45–47] As a high tech that is currently developing rapidly, artificial intelligence is one of the core technologies to realize smart grids. It is an effective means for new power grids to overcome existing difficulties and achieve long-term development.[48]

Driven by the needs of economic development, the world power grid is gradually moving towards a new type of power grid characterized by safety, efficiency, clean and low-carbon, flexibility, and intelligent integration. The smart grid will run through every link of the new power system and is the key to the formation of energy Internet.[49] Smart grid can rely on different types of technologies, enhance the "defense force" of power grid operation, timely avoid the damage of various factors to the power grid and power system, increase the proportion of new energy generation, collect very comprehensive power grid operation parameters, will play a very critical role in the process of new power grid planning and construction. It is foreseeable that smart grids with open interconnection, multi-source collaboration, multi-energy complementarity, and deep coupling of energy and information will be the main morphological characteristics of the future energy power system. As shown in Table 1, new power grids have significant advantages in self-healing, reliability, compatibility, high efficiency, and interactivity compared with the traditional grid.

2.2 | The critical issues faced in the future and the potential application prospects of TENG

With the changes in the energy structure, new challenges have been put forward to the operation of the power grid. First, new energy power generation will form a distributed power generation structure. Suppose the capacity or location of the new energy power supply access to the distribution grid is not appropriate. In that case, the power grid's loss will increase, triggering voltage fluctuations and even the misoperation of protective equipment.[36] At the same time, with distributed energy connected to the grid, the topology of the infrastructure of the power system will change, and the new power grid must handle unstable power generation from renewable energy and other distributed power supply. How to integrate new energy power into the distribution network efficiently is the main problem we are facing at present.

There are some critical problems when the microgrid is connected to the distribution grid, such as the adjustment of the power supply strategy during the operation of "island operation" and the increase of difficulty in power flow prediction.[50] Meanwhile, the expansion of smart distribution networks also has the problems of deployment strategy of advanced grid technology and integrated technology, coordinated development of microgrid and large grid, as well as complex and diverse coordination control and diverse power consumption and power demand.[49] Electric vehicle access will also bring many challenges to the power system. As the charging pile increases, the power distribution transformer may be overloaded, resulting in a decline in nearby electric energy quality, increasing the possibility of power outages, and making the life of the distribution line and transformer significantly reduced.[51] At the same time, the application of these emerging technologies is still in

TABLE 1 Difference between traditional grids and future new power grids.

Features	Traditional power grid	New power grid
Self-healing	Cannot position the location of the failure in time; power supply recovery depends on the manual	Real-time monitoring of the power grid to reduce the incidence of failure; Quickly locate the fault location and automatically isolate it to avoid a large-scale power outage
Reliability	Poor reliability, prone to widespread power outages	Real-time monitoring and evaluation of power grid operation status can significantly improve the ability to withstand natural disasters and cyber attacks
Compatibility	Large-scale centralized power generation cannot adapt to the access of small, distributed power sources	With new energy as the main power supply, a large number of small power generation equipment and energy storage equipment can be allowed to access
High efficiency	The operation efficiency of the power grid is affected by many factors, such as the labor force and system	Using digital information technology to realize optimal dynamic allocation of power resources and improve the efficiency of power grid operation
Interactivity	The end user is only a single consumer, and the user has little information interaction with the power company	Users can know the change in electricity price in real-time, use electricity reasonably, and make use of the difference in electricity price in different periods for electricity trading, transforming from a single consumer to a participant in electricity trading

its infancy. Forming a complete and mature systemic technology system takes a long time, and further research is needed.

At present, the monitoring of the power system depends mainly on the Supervisory Control and Data Acquisition (SCADA) system. Predictably, smarter networking technologies will play a more critical role in enabling joint monitoring on a larger scale.[44] Applying artificial intelligence (AI) technology and increased communication between the IoTs infrastructure may also bring obvious network security challenges to the new power grid. In addition, the Internet of Things applications in new power grids are generally distributed on a large scale, so its modeling and simulation will be an essential and challenging task. Self-healing is a vital attribute of a new power grid. For the complexity and intelligent needs of the distribution network, the self-healing control system needs to have high intelligence and computing technologies to support it.

The core of the construction of new power grids is to break through the research and technological innovation of key technologies of electrical information, such as smart grid scheduling optimization, smart grid load prediction, intelligent monitoring, and fault analysis of power systems. It is necessary to promote AI to be more efficient and accurate in solving complex problems in new power grids and improve the research and development quality of cutting-edge technology of smart grids.[51] In addition, the control of the new power grid system will become more complicated. In addition to the substation, it is necessary to establish a monitoring system along the feeder.[52] From a computing perspective, the new power grid is a computer and power infrastructure network that aims to monitor and control the efficient use of all types of energy.[53]

In summary, in new power grids, intelligent monitoring, intelligent scheduling, and rapid provision of solutions in the power system's operating state are the three urgent issues currently urgently needed. However, whether it is the innovation of the power grid structure, the invention of control methods, or the application of network technology, it is necessary to analyze the power grid data in detail, compare it with the stored information, and finally make decisions. In these processes, an extensive and widely arranged large-scale sensing network cannot be separated. However, the defects of the traditional battery-powered power supply, such as high cost, large energy consumption, long-term maintenance, environmental pollution caused by waste batteries, and inapplicability in some areas, limit the development of the new power grid and related technologies to a certain extent.[10–13] Therefore, overcoming the problems faced by sensors and equipment in special environments used in traditional power grids will undoubtedly greatly promote the rapid development of new power systems and related fields.

As an emerging energy collection technology in recent years, TENG has the advantages of comprehensive material sources, low-cost, high-energy conversion efficiency, simple structure, and can effectively collect low-frequency energy in the environment.[54] As an emerging energy harvesting technology in recent years, TENG has shown unique advantages over other environmental energy harvesting technologies, as shown in Table 2. It also has advantages such as wide material sources, low-cost, simple structure, etc., and can effectively collect low-frequency energy in the environment [55]. TENG has shown great development prospects and has been initially applied in the condition detection of electrical equipment [56]. It provides a very promising solution to solve the above problems. It shows excellent development prospects and has reached the preliminary application in monitoring electrical equipment status.[55] TENG provides a promising solution to this problem.

3 | TENG'S THEORETICAL FOUNDATION AND OUTPUT CHARACTERISTICS

TENG is another critical application of Maxwell displacement current. To some extent, TENG affects the future development of the new power grid, the Internet of things, sensing technology, blue energy, big data, and other technical fields.[56] TENG has shown immense development potential in different areas. Understanding TENG's basic theory is essential for further improving TENG's output performance and finding a suitable application scenario. This chapter briefly introduces the theoretical foundation of TENG, as well as the working principles and control equations of four models of TENG, to help us choose the appropriate TENG structure and energy collection system, reduce the cost of the experiment, and avoid the output performance loss caused by design problems.

3.1 | TENG's theoretical foundation

People have always tried to propose a unified theoretical model to explain electromagnetic phenomena, such as action at a distance, molecular vortex models, etc. Nonetheless, they could not fully explain all the electromagnetic phenomena observed at that time. It was not until Maxwell proposed the displacement current theory in 1861.[57] On this basis, the unity of the electric and

TABLE 2 TENG compared with other environmental energy collecting devices.

Type	Advantage	Deficiency
Small Wind Turbines and Solar Cells	High-output power	High cost Large volume Still need batteries Strong output fluctuation
Electric Field Energy Harvesting Device	Continuous energy output	Low-output power Difficult installation Large volume required
Electromagnetic/RF Energy Harvesting Devices	Continuous energy output	Low-output power Susceptible to interference Work narrow frequency band
Electromagnetic Generator	High-output power Continuous energy output	Fire hazard Installation difficulty High-temperature hazard
Pyroelectric Nanogenerator	Continuous energy output	Low-output power Material fragility
Piezoelectric Nanogenerator	Simple structure Continuous energy output Harvesting multiple energies	The mechanical durability of piezoelectric crystal is insufficient
Triboelectric Nanogenerator	Strong durability Continuous energy output Harvesting multiple energies	Triboelectrification materials are susceptible to contamination Output power needs to be further improved

magnetic fields was achieved by the Equation of 20 descriptions of the electrical field and magnetic field behavior.[58] 20 years after Professor Maxwell's death, British scientist Oliver Heaviside and German scientist Heinrich Hertz organized the 20 equations proposed by Maxwell into four equations.[59] However, they referred to it as Maxwell's equations. Maxwell's equations concentrated on Gauss's Law, Gauss's Law of Magnetism, Maxwell-Ampere's Law, and Faraday's electromagnetic induction law. It is one of the most important equations in physics. The expression is as follows:

$$\begin{aligned} &\nabla \cdot D = \rho \\ &\nabla \cdot B = 0 \\ &\nabla \times E = -\frac{\partial B}{\partial t} \\ &\nabla \times H = J + \frac{\partial D}{\partial t} \end{aligned} \tag{1}$$

It should be pointed out that the Equation (1) can be established on the condition that the medium's volume, surface, and spatial distribution do not change with time. Among them $D = \varepsilon_0 E + P$ represents polarization field density. $\frac{\partial D}{\partial t}$ represents the displacement current generated by the time-varying electric field and electric field-induced electrical polarization. The displacement current is not the current generated by free charge motion but the electric field (vacuum or medium) that changes over time, the tiny movement of electric charge bound in an atom, and the polarization of the electrical medium in the material. The Maxwell Formula Group was hailed as another outstanding achievement after Newtonian mechanics. It has laid a solid foundation for the rapid development of society.

With the emergence of TENG and the further development of related fields, researchers have found that Maxwell's positioning current theory applies to TENG.[60] Benefit from the coupling effect of contact electrification and electrostatic induction, the triboelectric charge generated by the two different media surfaces during physical contact. When the two surfaces are separated, the contact-induced triboelectric charge creates a potential difference that drives electrons between the two electrodes. To facilitate the output performance analysis and actual engineering application of TENG, Wang Zhong Lin in 2017, used the Galilean transformation to process the expression of displacement current in Maxwell's equations under conditions far below the speed of light.[62] An additional polarization term P_s is introduced into the electric displacement vector D:

$$D = \varepsilon_0 E + P + P_s \tag{2}$$

Among them, the first polarization vector P was due to the existence of the external electric field, and the surface charge and external mechanical disturbance process of the exposure of the electrical effect mainly caused the additional item P_s. Bring Equation (2) into the Maxwell Formula Group, and define it at the same time:

$$D' = \varepsilon_0 E + P \tag{3}$$

At this time, the processed Maxwell equations are[61]:

$$\begin{aligned} \nabla \cdot D' &= \rho' \\ \nabla \cdot B &= 0 \\ \nabla \times E &= -\frac{\partial B}{\partial t} \\ \nabla \times H &= J' + \frac{\partial D'}{\partial t} \end{aligned} \tag{4}$$

Among them, the volume charge density and current density are redefined as:

$$\begin{aligned} \rho' &= \rho - \nabla \cdot P_s \\ J' &= J + \frac{\partial P_s}{\partial t} \end{aligned} \tag{5}$$

It meets the law of conservation and continuous Equation:

$$\nabla \cdot J' + \frac{\partial \rho'}{\partial t} = 0 \tag{6}$$

In Equations (4) and (5), the conduction current is J, and the general displacement current is:

$$J_D = \frac{\partial D'}{\partial t} + \frac{\partial P_s}{\partial t} \tag{7}$$

Among them, $\frac{\partial P_s}{\partial t}$ is the current generated by the boundary change of the medium, which is the theoretical source of the nanogenerator. In addition to its contribution to capacitors, the processed Maxwell equations further promote the development of new energy technologies and self-powered sensors. It has widely used items in the Internet of Things sensor network, energy harvesting, and equipment condition monitoring. It is another important application of Maxwell's equations in energy and sensors after electromagnetic field.[14,56]

3.2 | TENG's four basic working modes and their output performance

In recent years, with the continuous deepening of TENG research, many researchers have successfully constructed TENG with various new structures. According to different structures and movement patterns, TENG can be divided into vertical contact-separation mode, in-plane sliding mode, single-electrode mode, and free-standing triboelectric-layer mode. This article classifies TENG according to its different electrostatic induction processes and analyzes its essential output characteristics (opening voltage (V_{OC}), short-circuit transfer charge (Q_{SC}), and inherent capacitor (C)). Due to the wide selection of friction materials for TENG, different materials have different characteristics, so we mainly analyze the widely used dielectric–dielectric and metal–dielectric types here.

Based on the theory of electromagnetic fields, TENG can be regarded as a combination of multiple capacitors. So fundamentally, TENG has capacitive behavior characteristics. We can simplify any structure into a pair of friction layers that move under the action of external forces and the electrodes on their backs. When a couple of triboelectric layers are in contact, the same number of different charges will be generated on the surface of the two triboelectric layers. The voltage generated by the triboelectric charge between the two electrodes (V_{OC})depends on the separation distance (x) between the triboelectric layers. At the same time, the action of V_{OC}, the two electrodes connected by the external circuit will generate a certain amount of transferred charge ($+Q/-Q$). The voltage generated by these transferred charges between the two electrodes is $-\frac{Q}{C(x)}$, where C represents the capacitance between electrodes. Therefore, the voltage between two electrodes of TENG is:

$$V = -\frac{Q}{C(x)} + V_{OC}(x) \tag{8}$$

The Equation (8) is known as the governing equation for TENG and the $V-Q-x$ relation for TENG.

3.2.1 | Vertical contact-separation mode

As the earliest proposed working mode for TENG, the Vertical contact-separation mode structure is simple and suitable for most types of motion. It is made by stacking two dielectric materials with the thickness of d_1 and d_2, with the relative dielectric constant of ε_{r1} and ε_{r2}, respectively, and the metal electrodes on the back. Its model is shown in Figure 2.[63] When the triboelectric layers are in contact under mechanical disturbances, the surface of the two triboelectric layers will be contacted to generate the electrostatic charge (triboelectric charge) of density σ. We assume that the attenuation of the surface charge of the triboelectric material can be ignored, and it is evenly distributed on the surface of the dielectric.[64] Since the size of the metal electrode (S) is much larger than the separation distance between them (d_1+d_2+x), Since the separation distance between electrodes (d_1+d_2+x) is far less than its area size (S), we use a plate capacitor model for analysis.

Based on the above models and basic assumptions, the $V-Q-x$ relation and basic output characteristics can be deduced by electrodynamics:

$$\begin{aligned} V &= -\frac{Q}{S\varepsilon_0}(d_0+x(t))+\frac{\sigma x(t)}{\varepsilon_0} \\ V_{OC} &= \frac{\sigma x(t)}{\varepsilon_0} \\ Q_{SC} &= \frac{S\sigma x(t)}{d_0+x(t)} \\ C &= \frac{\varepsilon_0 S}{d_0+x(t)} \end{aligned} \tag{9}$$

where d_0 is the effective dielectric thickness, which is the sum of all the dielectric thickness d_i between two metal electrodes divided by their relative dielectric constant ε_{ri}, as shown below:

$$d_0=\sum_{i=1}^{n}\frac{d_i}{\varepsilon_{ri}} \tag{10}$$

Through the above derivation, it can be seen that V_{OC} is proportional to x and $C$is inversely proportional to x. Because the triboelectric material is usually thin, to achieve a high charge transfer efficiency, the triboelectric layers must be in close contact. In addition, when x increases enough to be comparable to the area size (S) of the friction layer, the electrode cannot be regarded as infinite, and the edge effect will affect the linear relationship between the open-circuit voltage (V_{OC}) and the separation distance x.

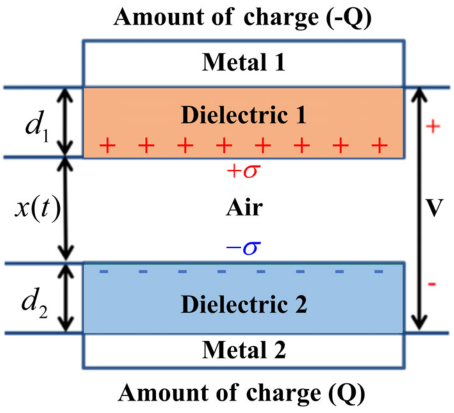

FIGURE 2 Dielectric–dielectric vertical contact-separation TENG.

3.2.2 | In-plane sliding mode

The output performance of the in-plane sliding mode TENG is better than vertical-contact separation mode TENG, but the wear of the triboelectric layer is more serious. The length of the two dielectric materials is l, the width is w, the thickness is $d_i (i=1,\ 2)$, and the metal layer of the back of the two dielectric materials is used as an electrode, as shown in Figure 3.[65] The top dielectric layer can slide along the transverse, and the transverse sliding distance is x. After sliding, the surface of dielectrics will appear with equal amounts of heterogeneous charges in the non-overlapping region. We also assume that the dielectric surface charge attenuation is ignored and is evenly distributed on the surface of the dielectric.[63] Since the centers of positive and negative triboelectric charge are at the atomic level, the total density of the charge on the overlapping surface can be viewed as 0.

Under normal circumstances, the $V-Q-x$ relation of the approximate analytic equation can be obtained by ignoring the edge effect. As long as the two triboelectric layers are not completely separated, the capacitors between the overlapping areas are the main part of the total capacitance. Therefore, the entire capacitor can be obtained from the following formula:

$$C=\frac{\varepsilon_0 w(l-x)}{d_0} \tag{11}$$

In the ideal case, non-overlapping regions have surface charge density is σ. The charge density is still uniform for the overlapped area. The charge distribution under open circuit conditions can be approximated by the following formula:

For non-overlapping areas of the bottom electrode:

$$\rho=\sigma \tag{12}$$

For the overlap area of the bottom electrode:

$$\rho=-\frac{\sigma x}{l-x} \tag{13}$$

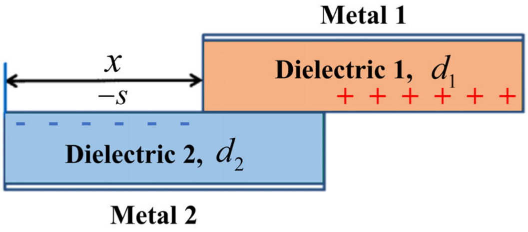

FIGURE 3 Dielectric–dielectric in-plane model TENG.

For non-overlapping areas of top electrodes:

$$\rho = -\sigma \tag{14}$$

For the overlapping area of the top electrode:

$$\rho = \frac{\sigma x}{l - x} \tag{15}$$

Using the charge distribution above and Gauss's Law V_{OC} can be estimated as:

$$V_{OC} = \frac{\sigma x d_0}{\varepsilon_0 (l - x)} \tag{16}$$

Therefore, when the edge effect is ignored, the $V - Q - x$ relation of the in-plane sliding mode TENG can be expressed as:

$$V = -\frac{1}{C}Q + V_{OC} = -\frac{d_0}{w\varepsilon_0 (l - x)}Q + \frac{\sigma d_0 x}{\varepsilon_0 (l - x)}s \tag{17}$$

Therefore, Q_{SC} is positively correlated with x, and $C(x)$ is negatively correlated with $(l - x)$. As x approaches l, C decreases sharply resulting in a sharp increase in V_{OC}. Moreover, the distance between triboelectric layers will greatly affect the output performance.

3.2.3 | Single-electrode mode TENG

For the TENG of the above two modes, the moving part needs to be connected with a wire to output electrical energy, which limits its applicability in some aspects. To overcome this limitation, the researchers proposed a single-electrode mode TENG and a free-standing triboelectric-layer mode TENG. Only one dielectric material has a back electrode in the single-electrode mode TENG, while the reference electrode can be placed in any position and does not need to be connected with the dielectric material. To simplify numerical calculations, we use a two-dimensional model for analysis without losing the inherent physical characteristics, as shown in Figure 4A.[66] The length of the triboelectric layer is l and the width is w. The thickness of dielectric 1 is d_0 and the thickness of the main electrode is d_m, and the reference electrode of the same size is located below the main electrode, spaced g apart. The two electrodes are fixed, and the distance between the triboelectric layers is x. Due to triboelectrification with the main electrode, the bottom surface of dielectric 1 is σ. We also assume that the dielectric surface charge is evenly distributed on the dielectric surface and its attenuation is negligible, so there will be an equal amount of positive charge ($\sigma \omega l$) distributed on the main electrode. Due to the fixed electrode, the inherent capacitance C of the single-electrode mode TENG almost does not change with the increase of separation distance x. When dielectric 1 is far from the electrode, it has little influence on the electric field distribution around it. Therefore, the open-circuit voltage V_{OC} reaches saturation quickly with the increase of the x, while the short-circuit transfer charge Q_{SC} reaches saturation slowly. In theory, when dielectric 1 is infinitely far away from the main electrode, the potential of the two electrodes is the same, and the induced charge generated is evenly distributed between the two electrodes, so the maximum short-circuit charge transfer rateη_{CT} can only reach 50%. Therefore, compared with the TENG of other modes, the single-electrode mode TENG output performance is lower.

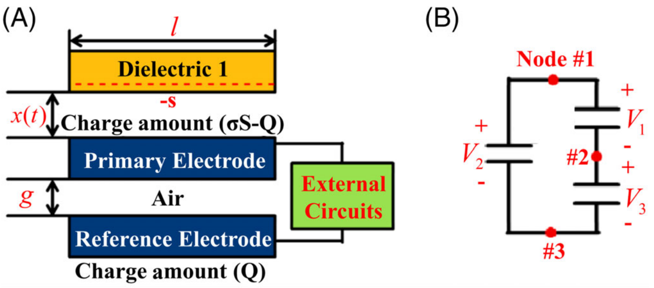

FIGURE 4 Single-electrode mode TENG. Copyright 2014, John Wiley and Sons.[66] (A) Mental-Dielectric Single-Electrode mode TENG. (B) Single-electrode TENG equivalent circuit model containing three capacitors under open-circuit conditions.

We analyze it in the electrostatic system to fully display its inherent physical properties and output characteristics. In the above system, under the open-circuit condition, the electric potential of the whole bottom surface of dielectric 1 is almost unchanged, so we assume it is a Node (Node 1). Similarly, the main and reference electrodes are recorded as nodes 2 (Node 2) and 3 (Node 3). Each of the two nodes is equivalent to a capacitor, as shown in Figure 4B.[66] The capacitors C_1, C_2, and C_3only represent the capacitance effect generated directly by the electric field connection between the two nodes (without the electrostatic shielding effect), so they do not reflect the actual capacitance between the two nodes. For example, the actual capacitance (C_b) is:

$$C_b = C_2 + \frac{C_1 C_3}{C_1 + C_3} \tag{18}$$

Similarly, the actual capacitors between Nodes 1, 2, and 3 are:

$$C_a = C_1 + \frac{C_2 C_3}{C_2 + C_3} \tag{19}$$

$$C_0 = C_3 + \frac{C_1 C_2}{C_1 + C_2} \tag{20}$$

Under the open-circuit condition, the total charge on Nodes 1, 2, and 3 is $-\sigma\omega l$, $\sigma\omega l$ and 0, respectively., Q_{SC}, and η_{CT}can be given by the following formula:

$$\begin{aligned} Q_{SC} &= \frac{\sigma\omega l}{1+(C_1(x)/C_2(x))} - \frac{\sigma\omega l}{1+(C_1(x=0)/C_2(x=0))} \\ &= \frac{\sigma\omega l}{1+(C_1(x)/C_2(x))} \end{aligned} \tag{21}$$

$$\eta_{CT} = \frac{Q_{SC}}{\sigma\omega l} = \frac{1}{1+(C_1(x)/C_2(x))} \tag{22}$$

$$V_{OC} = \frac{\sigma\omega l C_2}{C_1 C_2 + C_2 C_3 + C_3 C_1} \tag{23}$$

where $C_1(x=0)$ approaches infinity.

When $x=0$, C_1/C_2 is infinite, and no charge transfer occurs. As x goes to infinity, C_1/C_2 approaches 1. In this case, $\eta_{CT}$is only 50%. We can observe that the capacitor C_2 is critical to V_{OC} and Q_{SC}. C_2 represents the capacitance effect formed when an electric field directly connects Node 1 and Node 3 without being affected by the electrostatic shielding of Node 2. If consider the electrostatic shielding of the main electrode, C_2 will be equal to 0 (the main electrode shields the electrostatic field), resulting in no output from the single-electrode mode TENG.

3.2.4 | Free-standing triboelectric-layer mode TENG

Due to the electrostatic shielding of the main electrode, the η_{CT} of the single-electrode mode TENG can only reach 50%. The researchers designed free-standing triboelectric-layer-based nanogenerators (FTENGs) to overcome this defect. According to their structural characteristics, FTENGs can divide into contact-mode FTENGs and sliding-node FTENGs. We first analyzed contact-mode FTENGs; their typical structure is shown in Figure 5A.[67] The dielectric layer (thickness: d_1, relative dielectric constant: ε_{r1}) is stacked with two metal layers. The metal layer simultaneously serves as the triboelectric material and electrode, forming two pairs of triboelectric layers. The distance between the two metal layers is g. Under the action of external force, when the two metal layers contact the dielectric layer, the surfaces of the metal layer will generate triboelectric charges. To simplify the analysis, we assume that the triboelectric charge density ($-\sigma$) generated by the surfaces of the metal layer is the same, so the total number of positive charges carried by the two metals is the same. As shown in Figure 5B, we also analyze it in the electrostatic system.[67] Based on the above assumptions, we can regard the potential of the metal layer 1, the metal layer 2, and the surfaces of the dielectric layer as a constant and use it as four nodes in the electrostatic system. Because Node 2 completely blocks the electrical connection between Nodes 1 and 3, there are only three equivalent capacitors in this model. The relationship between them is:

$$C = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}} = \frac{\varepsilon_0}{d_0 + g} \tag{24}$$

Under short-circuit conditions, we assume that the total charge on metal layer 1 is Q_1, and the total charge on metal layer 2 is Q_2 ($Q_2 = 2\sigma S - Q_1$). Meanwhile, C_2 can be regarded as infinite since the d_0 is much less than g in practical applications. According to electrodynamics and the law of conservation of charge, we can get the following:

$$Q_1 \approx \sigma S \frac{\frac{2}{C_3}}{\frac{1}{C_1}+\frac{1}{C_3}} = \frac{2\sigma S}{1+\frac{C_3}{C_1}} \tag{25}$$

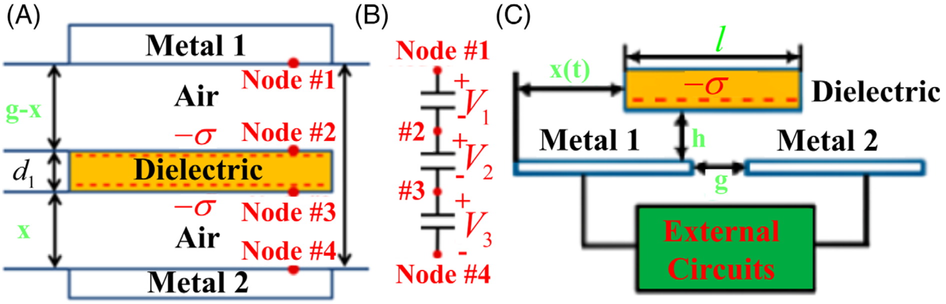

FIGURE 5 Free-standing triboelectric-layer mode TENG. Copyright 2015, Elsevier.[67] (A) Metal-dielectric contact-mode FTENGs. (B) FTENGs equivalent circuit model containing three capacitors under the open-circuit conditions. (C) Metal-dielectric sliding-mode FTENGs.

$$Q_2 \approx \frac{2\sigma S}{1+\frac{C_1}{C_3}} \tag{26}$$

Therefore, when the dielectric vibrates in the air gap, the charge will flow alternately between the metal layer 1 and the metal layer 2 to form a current because of the change of C_1/C_3, which is the basic working principle of contact-mode FTENGs. Its $V-Q-x$ relation is:

$$V=-\frac{1}{C}Q+V_{OC}=-\frac{d_0+g}{\varepsilon_0 S}Q+\frac{2\sigma x}{\varepsilon_0} \tag{27}$$

Sliding-mode FTENG is shown in Figure 5C.[67] Metal electrodes 1 and 2 with a gap g are placed in the same horizontal plane. A free-standing triboelectric layer containing only one layer of dielectric of the same size as the metal electrode is placed at a height h from the top of the metal electrode with a width w. We also use nodes to analyze it in the electrostatic system. Since the potential of the bottom surface of the electrical substance is not constant and the principle of superposition of the potential is needed to analyze. First, we take a small part of a region with a distance of k from the left edge of the bottom surface of the dielectric, its area is dk, the surface triboelectric charge density is $-\sigma$, and the total charge on the corresponding metal electrodes 1 and 2 is $\sigma\omega$dk. The dielectric charges (dQ_1 and dQ_2) of metal electrodes 1 and 2 under short circuit, the following formula can give conditions:

$$dQ_1=\frac{\sigma w dk}{1+(C_2(k)/C_1(k))} \tag{28}$$

$$dQ_2=\frac{\sigma w dk}{1+(C_1(k)/C_2(k))} \tag{29}$$

where $C_i(k)$ represents the capacitance between this small surface and the metal electrode i.

According to the electrostatic field superposition principle, considering all the charges on the surface of the dielectric, the total charge on metal electrodes 1 and 2 is the integral of each small region of triboelectric charge, which can be expressed as:

$$Q_1=\sigma w\int_0^l \frac{dk}{1+(C_2(k)/C_1(k))} \tag{30}$$

$$Q_2=\sigma w\int_0^l \frac{dk}{1+(C_1(k)/C_2(k))} \tag{31}$$

Therefore, $Q_{SC,final}$ can be expressed as:

$$Q_{SC,final}=\int_0^l \frac{\sigma w dk}{1+(C_2(k)/C_1(k))_{x=g+l}}-\int_0^l \frac{\sigma w dk}{1+(C_2(k)/C_1(k))_{x=0}} \tag{32}$$

When $x=0$, the lower surface of the dielectric is closer to metal electrode 1 than metal electrode 2. So for all values of k, $C_2(k)/C_1(k)$ is close to 0, so Q_1 is approximately σwl and Q_2 is approximately 0. And at $x=g+l$, for all k values, $C_2(k)/C_1(k)$ is going to be close to infinity. So Q_1 is close to 0 and Q_2 is close to σwl. Therefore, $Q_{SC,final}$ can reach σwl, in which case the η_{CT} can reach 100%.

In summary, to adapt to different working environments, researchers have developed different modes to meet the needs. However, in essence, TENG of different modes is the coupling effect of triboelectrification and electrostatic induction. By triboelectrification, the dielectric surface generates triboelectric charges, and the equivalent capacitance is formed between the charged dielectric and the metal electrode. Under the short-circuit condition, when the position of the dielectric changes, the size of each equivalent capacitance will also change, and then promote the movement of electrons between the electrodes so that the potential between the electrodes can be re-balanced, and this process generates current.

4 | TENG APPLICATIONS IN MAGNETIC FIELD UTILIZATION

With the Industrial Revolution 4.0, wireless internet technology has developed rapidly. Smart grid, the Internet of Things, and other fields based on this technology show excellent prospects for development. Large-scale sensor networks need to be constructed to promote further the practical application of research results in these fields. To obtain the necessary operating data for the control system, how to supply power to these enormous amounts of sensors is the first problem we must consider. In recent years, TENG has been used for power supply for small electronic devices because of its efficiency, economy, and pollution-free advantages. It has achieved a certain degree of development.[14]

As the most commonly used transmission equipment, overhead lines are widely distributed, and with the continuous development of transmission technology and scheduling strategy, they can maintain stable and continuous operation most of the time, especially the transmission lines with higher voltage levels. Transmission lines with higher voltage levels can run at hundreds or even thousands of amperes, and the alternating magnetic field energy generated around them will be extremely rich. In addition, the physical nodes that need to be monitored in the power system and the Internet of Things are usually some electrical equipment with large capacity, and rich alternating magnetic fields are generated around it when it is running. Therefore, alternating magnetic field is a widely distributed, stable, and easy to obtain Energy source in the surrounding environment of power system, and magnetic field energy Harvesting (MEHTENG) has been further developed.[27-31] As shown in Figure 6, TENG can collect not only stray AC magnetic energy widely used in daily life and convert it into electric energy to power various sensor devices, but also use the magnetic field as a driving force to reflect changes in the magnetic field through its output electrical signals, further realizing the design of self-powered sensor for monitoring magnetic field. In addition, when the traditional TENG is directly coupled with external mechanical coupling to obtain the driving force, the material wear causes the use of the service life and output performance of the material.[68-70] The researchers solved this problem using magnetic fields as an intermediate medium.[71-75] Therefore, we introduce some applications of the magnetic field-based TENG in self-powered sensors and micro/nano-power supply for sensor devices, which will provide a reference for the subsequent research on magnetic energy acquisition for transmission lines.

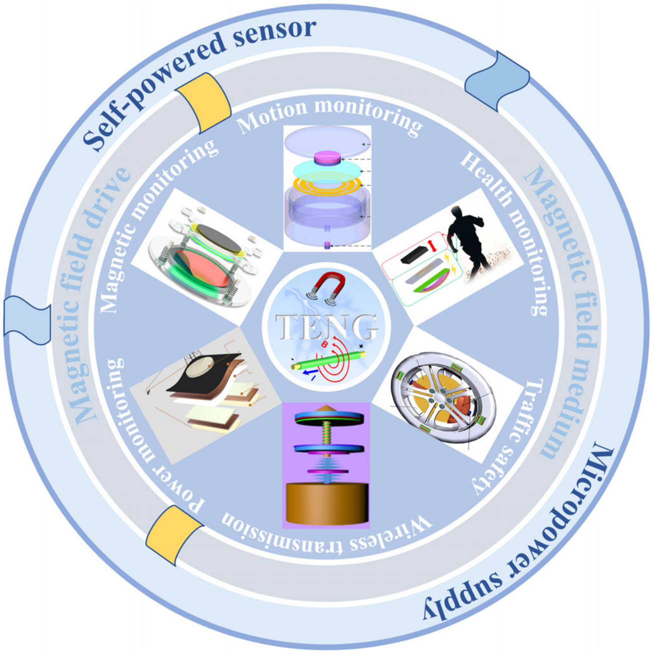

FIGURE 6 TENG using magnetic fields. Magnetic field monitoring self-powered sensor.[19] power grid monitoring sensor micro/nano-powered source. Copyright 2021, Elsevier.[77] Wireless energy transmission. Copyright 2019, John Wiley and Sons.[74] tire pressure monitoring sensor micro/nano-powered source.[73] health monitoring sensor micro/nano-powered source. Copyright 2017, Elsevier.[72] exercise detection self-powered sensor.[76]

4.1 | Self-powered sensors

Magnetic field exploration is of great significance for environmental monitoring, mineral exploration, medical application, and other areas.[78-81] Many magnetic field measurement technologies exist, such as the Hall effect, magnetic flux, superconducting quantum interference meter (SQUID), magnetic resistance, magnetic diode, or other semiconductor effects.[82] Some are used to detect changes in the strength of the magnetic field, while others are used to detect the direction of the magnetic field. However, all of these instruments need to be connected to the external power source. Due to the complex structure and essential nature of the power supply, the current detection equipment is not only bulky and lacks the necessary mobility. Therefore, the development of self-powered electromagnetic field monitoring sensors is imminent.

In 2012, Yang et al. proposed a TENG-based self-powered electromagnetic field sensor. Under the condition that the external power supply was not used, it could be used to monitor the changes in the magnetic field over time.[18] The structure is shown in Figure 7A-i. The TENG uses indium tin oxide (ITO) as the electrode, PET, and polydimethylsiloxane (PDMS) micro/nano-arrays as triboelectric materials, and a cantilever beam with metal (Fe) disc attached at one end as a magnetic field sensitive unit. When the strength of the external magnetic field changes, the magnetic force of the metal disc changes, which causes the TENG triboelectric layer to produce relative motion, and then outputs the electrical signal to monitor the magnetic field. As shown in Figure 7A-ii, exponential increase in sensor output voltage with increasing intensity of magnetic field variation, and the detection sensitivity of magnetic field change and magnetic field change rate is $0.0363\ \ln(mV)G^{-1}$ and $0.0497\ \ln(mV)G^{-1}$, respectively. By fitting the curve in Figure 7A-iii, the sensor's response time is about 0.13 s, and the reset time is about 0.34 s. Compared with the traditional magnetic sensor, it has a certain improvement. The self-powered electromagnetic field sensor designed by the author is the first application of TENG in magnetic field monitoring, which proves the feasibility and excellent performance of TENG in the field of magnetic field exploration.

However, sometimes we need to monitor both the strength and direction of the magnetic field. Although

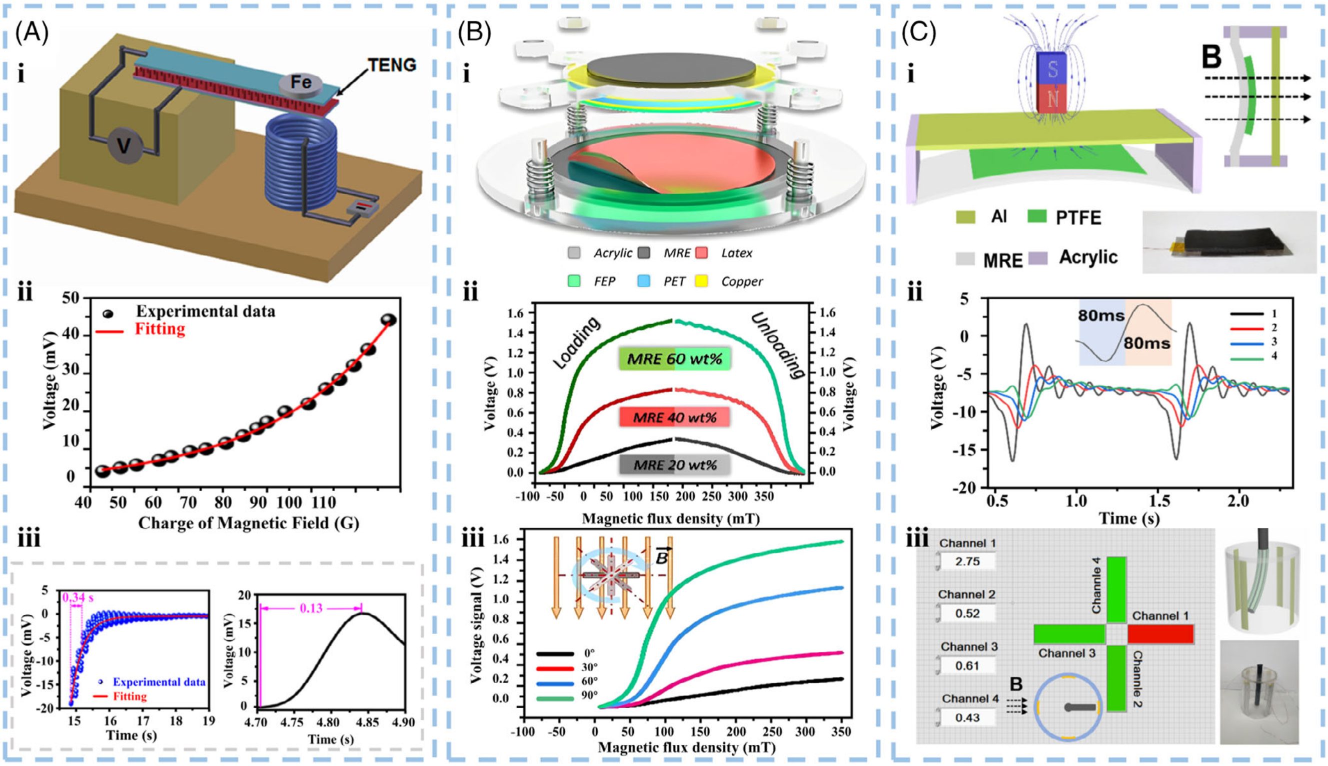

FIGURE 7 Magnetic field monitoring self-powered sensor of TENG is utilized. (A) A TENG self-powered sensor for monitoring changing magnetic fields. Copyright 2012, American Chemical Society.[18] (B) A self-supplying electromagnetic field sensor for time-varying and uniform magnetic field monitoring.[19] (C) A TENG self-powered sensor for magnetic field monitoring.[20]

Yang et al. can accurately measure the change of the magnetic field through the sensor's output voltage and have high detection sensitivity, However, there are still deficiencies in monitoring the strength and direction of the uniform magnetic field (UMF).[18] Like TENG, magnetorheological elastomer (MRE) has also received a lot of attention in recent years.[83-86] MER has excellent magnetic properties, and its deformation depends entirely on the external magnetic field.[20] Therefore, combining this with TENG's sensitivity to deformation can provide an effective measurement of UMFs monitoring.

In 2018, Qi et al. designed a TENG-based magnetic field sensor (TMFS) based on MRE and TENG, which can be used for both time-varying and time-invariant magnetic field monitoring.[19] The structure is shown in Figure 7B-i. The lower part is a deformed component composed of MRE containing 60 $wt\%CIPs$ (Carbonyl iron particles) and latex film with its surface as the positive triboelectric material. The top part is a TENG component. At the same time, to increase the deformation degree of MRE and to improve the performance of the sensor, the author completely fixes the other MRE thin film on the acrylic board of the TENG component. When applying an external magnetic field for TMFS, MRE's magnetic deformation will cause TENG to generate different output signals. Figure 7B-ii reflects the relationship between its output electrical signal and local magnetic field strength. These results are very similar to the performance of the sensor proposed by Yang et al., indicating that TMFS can be used to measure time-varying magnetic fields.[18] The action and reset time of TMFS are further improved to about 20 ms and 30 ms respectively, and the sensitivity of 16 $mVmT^{-1}$ can be reached in the magnetic field of 40-100mT. Figure 7B-iii shows the response capacity of TMFS to the different directions of the magnetic field. The amplitude output electrical signal increases with the angle increase. The intensity and direction of the UMF can be obtained by comparing the output performance of the TENG under different conditions. In addition, TMFS also shows the stability of continuous work for a long time. Based on MRE's excellent magnetic-deformation characteristics and the irreplaceability of TENG perceived displacement changes, TMFS shows stability and high sensitivity in magnetic field detection. These results suggest that TMFS has considerable development potential in terms of self-powered electromagnetic field measurement. A new method for detecting UMF is proposed.

In 2021, Wan et al. selected styrene ethylene butylene styrene (SEBS) powder,[20] liquid paraffin, and magnetic fluid in a 1:3:1 co-blending ratio of MRE film to construct an MRE-based TENG self-powered electromagnetic sensor, whose structural design is shown in Figure 7C-i. With the assistance of the LabView program, the author designed a TENG -based pointer 4-channel magnetic field sensor. A PTFE-covered MRE is mounted on the base to indicate the direction of the magnetic field. Figure 7C-ii shows the signal output when the magnet approaches channel 1, which shows the apparent rise of peak voltage, and its sensitivity is significantly improved. In less than 60 mT under the magnetic field strength, the sensitivity is 31.6 $mVmT^{-1}$. When the magnetic field intensity exceeds 60 mT, the sensitivity is 215 $mVmT^{-1}$, and the output shows good stability during 2000 contact-separation cycles. All these results show that the magnetic sensor designed by the authors is stability enough to work well under various working conditions. As can be seen from Figure 7C-iii, when the magnetic field was applied in a signal direction, the directional channel emits red light while the remaining channels remained unchanged in green. At the same time, the intensity of the magnetic field was calculated by analyzing the output voltage of each channel, and a highly sensitive magnetic field vector monitoring in four directions was achieved.

The above-mentioned work provides a new approach for the self-powered monitoring of the dynamic magnetic field. The application field of the TENG self-powered sensor is extended.

Due to the superiority measured in sports parameters,[11,87] the sports sensor plays an irreplaceable role in many fields, such as aerospace, condition detection, and smartphones. However, most commercial sports sensors can only rely on batteries or connecting cables to supply power. Therefore, there are defects such as harsh installation conditions, cumbersome maintenance, low economic efficiency, and environmental pollution caused by waste batteries.[12] Also, the energy consumption of numerous sensors is a non-negligible problem.[88] TENG-based multifunctional self-powered sensors are receiving increasing attention from academia and industry.

In 2015, HAN et al. designed a comprehensive tilt-angle measurement sensor based on magnetic auxiliary TENG.[89] A comprehensive inclination measurement can be achieved through the cooperation of the two sensors. The structure is shown in Figure 8A-i. The top magnet not only acts as the top electrode of the TENG and the magnetic field supply component of the electromagnetic generator but also repels the bottom magnet to provide power for the separation of the triboelectric layer of the TENG. Compared with the traditional mechanical restoring force, the mechanical fatigue of TENG components is effectively prevented. When the TENG tilts, the axial component of gravity of the magnet will decrease, and when the external excitation is the same, the distance and speed of the TENG contact separation will increase. The angle of the component can be obtained by analyzing the electrical signal output. Installing the two TENGs according to Figure 8A-ii on one cube can achieve comprehensive angle detection. At the same time, a corresponding system was built to achieve visualization of dip angle measurement, as shown in Figure 8A-iii, greatly simplifying the measurement process.

In 2018, Wu et al. proposed a TENG-based self-powered Multifunctional Motion Sensor (MFMS).[76] Its structure is shown in Figure 8B-i. A magnetic cylinder (MC) is installed in the housing directly below the Teflon plate, which together with the magnetic disc (MD) forms a magnetic control system that allows the sensor to return to its initial state in a short time for the next measurement. When MFMS moves, MD will slide on the PTFE board to induce the voltage output on the electrode. As shown in Figure 8B-ii, when MD does a linear movement in any direction, the electrostatic potential of the shard electrode reaches its respective peak when the MD passes so that the direction of the movement can be judged. At the same time, a temporal feature can be extracted and further analyzed to derive the acceleration. In practical applications, the MFMS can also achieve rotational speed measurement. From Figure 8B-iii, we can see that when the MD rotates clockwise, the open-circuit voltage waveforms of the circular arc electrodes reach their peak values in one cycle in turn, and the speed measurement can be achieved by analyzing the frequency of the output signals of the circular arc electrodes. Unlike commercial Angle sensing, MFMS is simple to assemble and more convenient to use. At the same time, MFMS not only reduces the size but also enables simultaneous measurement of multiple parameters.

In 2021, Ali Matin Nazar et al. designed a TENG (Magnetic Lift TENG, ML-TENG) with a magnetic suspension structure, using the exclusion force between magnets to separate the triboelectric layer.[90] As shown in Figure 8C-i, because the bottom of the actuator and the bottom of the base magnet polarity is the same, the side of M_3 and M_5 polarity is the same, when the actuator by external mechanical force into the base, M_5 will be pushed, when the external force is removed, the actuator under the action of the bottom magnet return, M_5 will also return, and then drive the friction layer components relative sliding. A self-powered speed sensor is developed using the ml-TENG, as shown in Figure 8C-ii. When vehicles pass by at different speeds, different levels of voltage signals will be output to get different speed signals, which provides a new idea for speed measurement in traffic detection.

In 2022, Jiao et al. designed magnetically circular layers TENG (MCl-TENG) with velocity induction and

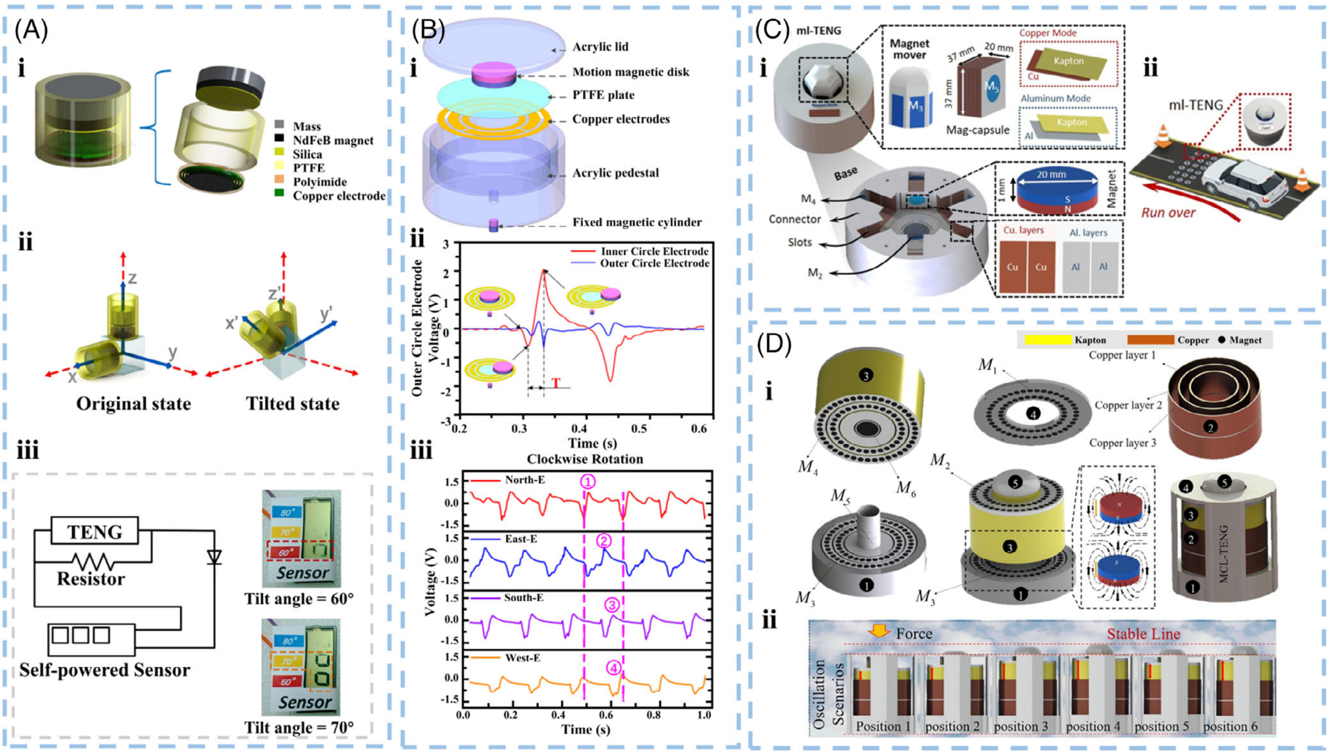

FIGURE 8 Self-powered sensor for motion detection based on the magnetic field using TENG. (A) An omnidirectional dip measurement sensor based on magnetic-assisted TENG.[89] (B) A self-powered multifunctional motion sensor based on TENG. Copyright 2018, American Chemical Society.[76] (C) A self-powered sensor based on a TENG-based maglev structure.[90] (D) A magnetic ring layer TENG is used for velocity sensing and damage detection. Copyright 2022, Elsevier.[91]

damage exploration, which can effectively respond to light loads. And it can detect velocity and cracks without complicated settings.[91] Figure 8D-i shows the structure of the TENG. Magnets M_1 and M_2 have the same magnetic poles, and M_4, M_6 and M_3, M_5 have the same magnetic poles, ensuring that component 3 can be suspended in the frame, and two modes of triboelectric layer structure are set up simultaneously for different purposes of measurement. The authors have developed a self-powered vehicle speed sensor and crack detection sensor based on the MCL-TENG. As shown in Figure 8D-ii, when the vehicle passes the MCL-TENG array, the vehicle speed can be obtained by analyzing the signal peak output of triboelectric mode 1. At the same time, due to different degrees of defects on the pavement, the vibration frequency generated by the road when the vehicle passes through the road will change. The signal of the output of the triboelectric mode 2 can obtain the road condition.

These studies have provided a practical path for TENG's applications in intelligent sports testing, expanded TENG's application field, and made important contributions to the development of self-powered sensors.

4.2 | Micro/nano-power supply for sensor devices

In recent years, the emerging technologies of power systems, such as new power grids and the electric Internet of Things, have attracted much attention. The running state perception of transmission lines and the parameter measurement of electrical equipment in the power grid are the keys to realizing the intelligent power system in construction. Status monitoring needs to collect real-time information on a large amount of equipment, and high sensor requirements are made for sensors.[92,93] The transmission line cannot directly power most sensors installed on the power transmission equipment in the power grid, and most work in a battery-powered. However, using numerous battery power supplies is not only very expensive but also the extreme environment charging and discharging efficiency decreases, and other problems limit the further development of smart grid sensor networks. Therefore, researchers have developed a number of energy harvesting devices for collecting the magnetic energy of transmission lines to power sensing devices and show excellent application prospects.[27-31]

The Magneto-mechano-electric (MME) generator can continuously collect power from the stray alternating magnetic fields (fixed frequency 50/60 Hz, less than 1 mT(10oe)) generated by power cables. It has attracted great attention in developing new power grids and self-powered sensing systems of the Internet of Things.[21,94,95]

In 2019, Lim et al. proposed a Magneto-mechano-triboelectric nanogenerator (MMTEG) that works in a weak magnetic field environment to power a positioning system by converting stray soft magnetic field energy into electric energy.[96] Figure 9A shows its working principle and structure. Perfluoroalkoxy (PFA) and aluminum foil serve as the triboelectric layers and NdFeB magnets as the counterweights and magnetic response components, a cantilever MMTEG assisted by NdFeB magnets was constructed, and magnetic energy capture under AC magnetic field is realized. To obtain a larger triboelectric region in the process of collecting magnetic energy, the structure of the device is designed to work in the best resonance mode by using the second-order bending resonance mode so that the voltage output is significantly improved. At the same time, the magnetic energy of alternating current can be captured at different frequencies by adjusting the weight of the counterweight magnet. The MMTEG designed by the author has significant durability, and the electrical output fluctuations in the 33 million cycles are less than 5%. The author charges the capacitor through the MMTEG under the AC magnetic field and then connects the IoT beacon to the capacitor. Beacon equipment can continuously emit position signals at intervals of 1 s. The designed MMTEG can continue to provide sufficient electrical energy for the IoT system without batteries.

Since the cantilever beam structure is capable of converting the energy in stray magnetic fields into mechanical vibrations, the researchers achieved the combination of a piezoelectric nanogenerator (PENG) and a magneto-mechano-triboelectric nanogenerator (MMTENG) by attaching the TENG to a piezoelectric device, further increasing the total power output.

In 2021 Yang et al. designed a hybrid piezo/triboelectric nanogenerator (HP/TENG) based on a cantilever beam structure to harvest magnetic energy.[97] The structure is shown in Figure 9B. The hybrid nanogenerator uses a Ti sheet as a cantilever beam with a circular structure of PENG on the upper side and a contact-

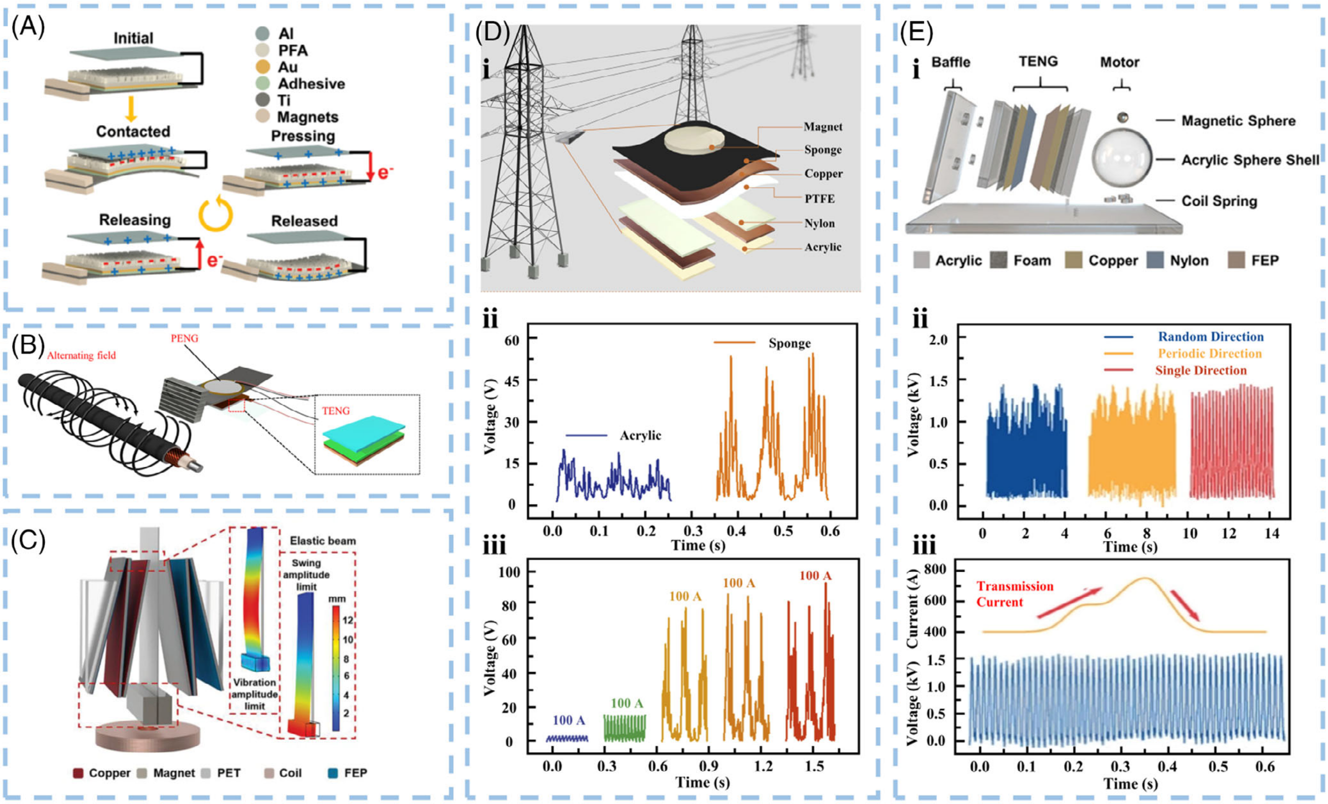

FIGURE 9 Micro/nano-powered source using TENG to collect magnetic energy from transmission lines. (A) An MMTEG operates in a weak magnetic field.[96] (B) An HP/TENG based on a cantilever beam structure. Copyright 2021, John Wiley and Sons.[97] (C) A hybrid friction electricity based on a flexible swing structure-electromagnetic energy collection device. Copyright 2022, John Wiley and Sons.[98] (D) An S-TENG for resisting fatigue. Copyright 2021, Elsevier.[77] (E) A rotational magnetic ball for TENG. Copyright 2021, John Wiley and Sons.[100]

separation TENG on the low side. Under the action of the applied magnetic field, the cantilever beam structure movement makes periodic contact and separation between the Al foil and PDMS film. At the same time, the PENG is alternately subjected to compressive and tensile stresses due to the cantilever beam deformation. The alternating flow of electrons forms the AC energy output. HP/TENG combines the advantages of TENG (low-frequency energy harvesting) and PENG (high output power). HP/TENG can directly supply power to electronic devices through energy management circuits. Continuous measurement and transmission of temperature and humidity data are realized. These results demonstrate the feasibility of HP/TENG as a micro/nano-power source and show the promise of mixing multiple types of energy harvesting technologies.

However, the expensive and time-consuming production process of piezoelectric crystals or woven magnetostrictive metals is a great challenge to promote the utilization of these single-crystal-based PENGs, and piezoelectric ceramics may lose their piezoelectricity due to insufficient mechanical durability for long-term operation.[24]

In 2022, Yuan et al. proposed a hybrid triboelectric-electromagnetic magnetic energy harvester (HMEH) based on a flexible pendulum structure, an electromagnetic generator (EMG) with an electromagnetic coil structure, a flexible pendulum, and two multi-layer TENGs constitute the HMEH device shown in Figure 9C.[98] The coil is located at the device base, which is connected to the magnet (NdFeB, N35) attached to the bottom of the cantilever beam. The multi-layer TENG unit composed of two pairs of contact-separation mode TENG is installed on both sides of the cantilever beam. Through detailed analysis of the action of force and momentum on the TENG unit, the authors found that as the mass of the block increased, the vibration became more chaotic, resulting in an irregular output waveform, and optimized the output waveform of the HMEH through the optimization of structural parameters. The TENG unit with a three-layer structure is also used to increase the pendulum's swing frequency, which increases the short-circuit current (I_{SC}) and can charge the capacitor more effectively. The introduction of EMG placed at the bottom further increased HMEH output. The author proposes the application concept of the self-powered wireless alarm system, including HMEH, wireless microcontroller, and power management circuit. HMEH can be used as the power supply of the transmission line temperature alarm. When the temperature reaches the threshold, the alarm will send an alarm signal to remind the operation and maintenance personnel, reducing the possibility of fire.

As a typical magnetic energy collecting structure, the cantilever beam can respond sensitively to the excitation from the alternating magnetic field by fixing the permanent magnet on the free end of the cantilever beam. However, cantilever beams based on permanent magnet resonance put strict requirements for the fatigue of fixed sections and essential working parts.[99] Considering the above problems, the researchers have proposed new structures, forward-looking routes, and methods that can maintain stable output performance under the impact of a large current.

In 2020, Yuan et al. proposed a swing-based anti-fatigue triboelectric nanogenerator (S-TENG) for magnetic energy collection.[77] The structure is shown in Figure 9D-i. Since the magnetic forces on both sides of the magnet are in opposite directions, the top layer is in alternating contact with the bottom layer when it swings in the alternating magnetic field. In such a continuous cycle, the external circuit continues to output AC electric energy. The author puts all components in a box to ensure the two triboelectric layers do not deviate from the original position. The unique structure of the non-rigid terminal avoids vibration fatigue while ensuring effective contact between the triboelectric layers. The hardness of the substrate is the main factor that affects the output performance. From Figure 9D-ii, we can see that after using the same weight sponge replacing the acrylic material, the output performance of the S-TENG has been greatly improved. But because beams without solid ends, the magnets may fall at different speeds and angles. The soft base amplifies this difference, resulting in multiple peaks in one cycle, increasing the output of the S-TENG by sacrificing the stability of the oscillating motion. As the current strength is applied, the substrate no longer maintains the level after the rebound, and the waveform will become uneven. However, it can be seen from Figure 9D-iii that the output performance of S-TENG was relatively stable even with a dynamic load on the power line. The traditional power supply will inevitably heat up when working. To ensure no damage to the equipment, it cannot work continuously for a long time. However, the heating of S-TENG is not obvious, and no folds caused by fatigue strain are found after the 100 h fatigue test, showing strong stability.

In 2022, Jin et al. designed and produced a rotational Magnetic Ball for TENG (RB-TENG) to capture the transmission line.[100] RB-TENG mainly consists of a drive unit, TENG unit, and baffle unit, as shown in Figure 9E-i. When the magnetic ball rotation speed reaches a certain value, under the effect of friction between the ball shells, the magnetic ball begins to roll along the inner wall of the ball. The centrifugal force generates by rotating to drive the TENG component contact separation. To better use the centrifugal force generated by the magnetic ball during the rotation process, three spiral springs were installed at the bottom of the acrylic ball to increase the stability of the acrylic ball shell. At the same time, a flexible connection is formed between the triboelectric layer and the base through the spring, which increases the contact area between the triboelectric layer and thus improves the power output of the TENG. Considering the dynamic change of the transmission line circuit, the author tests the stability of RB-TENG by setting a huge current impact. From Figure 9E-ii, we can see that under such a large current impact, the RB-TENG output performance does not obviously fluctuate, which indicates that RB-TENG can maintain excellent stability under such a shock current. It was evident from Figure 9E-iii that the unit could collect the magnetic energy efficiently without requiring precise control of the installation position. The author uses the temperature trigger and the dip trigger as the control unit and uses the RB-TENG to realize the power supply to the transmission line temperature and dip detection system. Due to its high output and extensibility, RB-TENG can be used to power sensing devices of different scales and has broad application potential in the fields of condition monitoring of transmission equipment, new power systems, and micro-power supply.

The above application of TENG in transmission line magnetic energy harvesting confirms the technical feasibility of TENG energy harvesting technology to power distributed self-powered transmission line monitoring sensors, demonstrates the infinite potential of magnetic field energy harvesting in self-powered wireless sensing systems, and broadens the application scenarios of TENG.

However, it is worth noting that external mechanical motion may lead to degeneration between the contact surface between the TENG device and the external motion components for a long time. In addition, the actual application environment will accompany different impurities, which may damage the surface of the electrodes and triboelectric layers with micro/nanoscale patterns. These problems will greatly reduce the output performance of the device, which is not conducive to TENG's actual application.[68-70]

In 2016, Huang et al. proposed and prepared a new magnetic auxiliary non-contact TENG.[71] The structure is shown in Figure 10A. By combining the magnetic response part with the TENG motion part, the non-contact mechanical motion remote control of TENG is realized. The magnetic-assisted non-contact model of TENG proposed by the author provides a feasible solution to the problem of aging and damage of TENG materials accelerated by environment and external excitation. And due to its non-contact advantages, the device provides new ideas for developing self-powered, non-damaged, non-invasive, and visual magnetic sensors. This non-contact-driven TENG also has the potential to transform some of the complex external mechanical movements into simple movements in typical TENG operating modes.

In recent years, micro-wearable electronic devices have been developed rapidly, wearable energy equipment has attracted more and more attention. Although we have realized the power supply to some light emitting diode (LED) from the human movement through TENG, the power generated is insufficient to continue driving wearable devices. By integrating TENG and EMG, the proposed hybrid nano generator provides a feasible way to solve the power supply problem of some wearable electronic devices with high power consumption.

In 2017, Ren et al. proposed a new non-contact electromagnetic-triboelectric hybrid nanogenerator driven by magnetic force, as shown in Figure 10B-i.[79] Creative embedding of magnetic Fe_3O_4 nanoparticles (NPs) into polyvinylidene fluoride (PVDF) fiber membranes as a triboelectric layer for harvesting biomechanical energy to drive portable electronic devices continuously. The hybrid nanogenerator consists of an EMG part and a TENG part. The energy output characteristics of the TENG and EMG differ significantly. The EMG produces a relatively high current and low voltage, while the TENG can obtain a lower current and higher voltage. After rectifying the AC signal through the energy management circuit, the mixed nanogenerator can output stable electric energy through the capacitor for the temperature and humidity meter and digital watch continuous power supply. Hybrid nanogenerators have better output performance than individual EMG or TENG units. The authors demonstrate a proposed hybrid triboelectric-electromagnetic nanogenerator for harvesting biokinetic energy from the human body, as shown in Figure 10B-ii. The designed hybrid nanogenerators provide an effective and sustainable power supply method for wearable electronic devices.

In the automotive industry, to ensure driving safety and air-combustion efficiency, the demand for tire pressure monitoring systems (TPMS) is increasingly urgent.[101,102] At present, wireless sensors, especially TPMS, are powered mainly by batteries, which are difficult to replace, limited durability, cause environmental pollution, and has other shortcomings.[10]

In 2018, Qian et al. designed a magnetically driven rotating triboelectric generator (M-TEG) with a magnetic seesaw structure and metal framework.[73] The structure is shown in Figure 10C. The 4 M-TEGs are evenly placed on the hub of the car. The permanent magnet installed on the brake pliers provides non-contact magnetic forces so that the M-TEG will generate a swinging motion

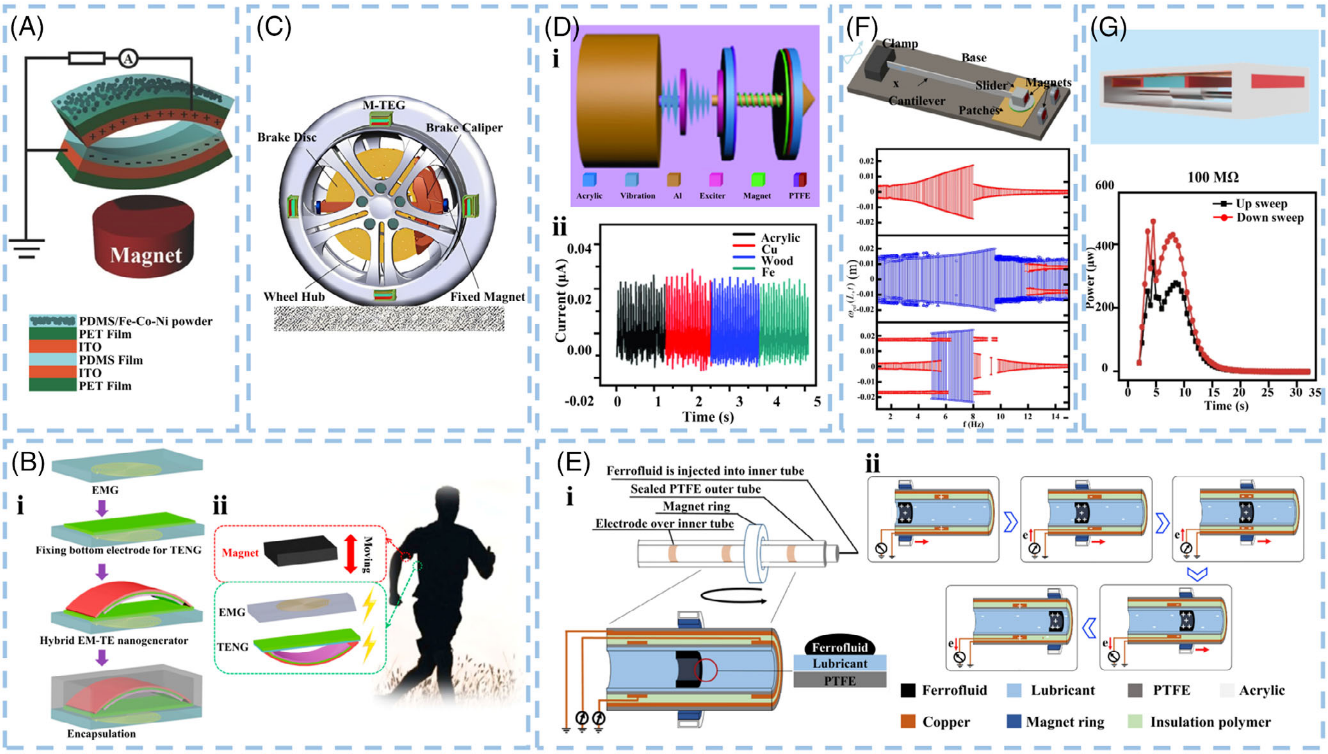

FIGURE 10 Self-powered sensor and micro/nano-powered source based on the magnetic field medium used by TENG to collect energy. (A) A new type of magnetic auxiliary non-contact TENG. Copyright 2016, John Wiley and Sons.[71] (B) A new type of magnetic-driven non-contact electromagnetic-triboelectric hybrid nanogenerator. Copyright 2017, Elsevier.[72] (C) An MTEG with a magnetic seesaw structure and metal framework.[73] (D) A non-contact wireless energy transmission technology based on TENG. Copyright 2019, John Wiley and Sons.[74] (E) A self-powered liquid level sensor based on TENG's magnetic auxiliary liquid–liquid interface. Copyright 2020, Elsevier.[75] (F) A sliding TENG operates under bistable conditions.[106] (G) A nonlinear friction nanogenerator with wide bandwidth.[107]

similar to a seesaw tire to the tire rotation. Multiple M-TEG placed symmetrically on the hub will not only affect the balance of the wheel, but also can provide power for TPMS, largely suppressing the influence of the huge centrifugal force under high-speed operation and it shows strong adaptability to different speeds, and after a long-time continuous rotation, M-TEG outputs voltage without obvious fluctuations. In addition, the metal structure and components of the M-TEG device can withstand physical wear and chemical corrosion. It can be seen that the designed M-TEG has excellent long-term working stability. To demonstrate that M-TEG has the potential to provide direct power to TPMS, the author uses the wireless temperature monitoring sensor system with the same component as the TPMS transmitter to test the performance of the M-TEG and successfully achieve data transmission. This research provides a new idea for the specific application of M-TEG in energy harvesting, tire pressure monitoring systems, and wireless sensor power supply.

Non-contact radio energy transmission is an ideal energy transfer technology because of its security and convenience.[103] Wireless power transmission technology has received a lot of attention and has achieved initial applications in certain areas.[104] However, most wireless power transfer methods based on electromagnetic induction are still facing the metal medium's energy transmission bottleneck. In addition, high facilities' cost and maintenance costs also limited the development of radio energy transmission. Therefore, developing a new technology that can be the reliable, convenient, and low-cost wireless transmission of electrical energy is essential.

In 2019, CAO et al. used the dynamic magnetic field medium to propose a TENG -based non-contact wireless energy transmission technology.[74] As shown in Figure 10D-i, wireless transmission of vibration energy is realized by using a permanent magnet. The vibration is converted into contact-separation motion of the triboelectric layers. In this way, electrical energy is first used to generate vibration. Through magnetic interactions, TENG can transmit vibration and output electrical signals through periodic contact separation between triboelectric layers, thereby realizing wireless transmission of electrical energy. In addition, the TENG designed by the author can obtain ideal output within a wide range of vibration frequency and magnet spacing, which has good adaptability and reliability. From Figure 10D-ii, we can see that although magnetoresistance is unavoidable in most non-ferrous media, the TENG designed by the authors shows only slight variations in output performance under magnetic interference from four typical materials, and it is still easy to light LED bulbs, clearly demonstrating the excellent effect of wireless power transmission. Good adjustable and adaptability means that the radio energy transmission system designed by the author can be widely used in power management and energy supply.

In 2020, Wang et al. designed a self-powered liquid level sensor based on the magnetically assisted liquid–liquid interface TENG, which overcomes the problem of the traditional liquid–solid interface TENG self-powered sensor remaining on the solid surface due to the excessive liquid velocity, resulting in the TENG output signal not being able to truly reflect the liquid movement.[75] An external magnetic field drives the water-based iron fluid in the tube without direct contact with the outside world,[105] which solves the problem of external environmental pollution affecting the output performance of the TENG. In addition, the lubricating oil layer is introduced between the iron fluid and the housing, which promotes the sliding of the iron fluid and expands the range of linear relationship between the iron fluid velocity and the TENG output, thus, the speed measurement range is improved. The structure is shown in Figure 10E-i, and the external magnetic ring drives the iron flow in the PTFE tube to generate an electric signal. From Figure 10E-ii, we can understand its working principle. Due to the different electrical negativity between the materials used, the negative charge generated by the friction is evenly distributed on the surface of the lubricant, and the electrons flow through the copper electrode. When the iron fluid with positive charges is close to the copper electrode, electrons generated by electrostatic induction flow from the bottom to the copper electrode. As the iron fluid moves away from the electrode, electrons flow from the copper electrode back to the underside. By analyzing the current signal on different electrodes, the position of the external magnetic ring can be obtained to get the height of the external liquid. At the same time, it can be recorded at the time when the output peak appears, and the speed of the outer liquid can be obtained. The author then tested it as a water level sensor in the simulated sewage environment and the output performance was the same, thus proving its advanced performance. This research provides a new way to solve the power supply problem of sensor equipment in a harsh environment. It is the first application of iron flow in non-contact TENG.

These studies are based on the magnetic-driven design, which enables the separation of the TENG from the external mechanical motion, avoiding the degradation of output performance caused by long-term direct contact between the device and the outer mechanical motion part.

Although after a period of development, various working modes and structures of TENG have been studied to some extent and showed excellent output performance. However, many TENG's power output and conversion efficiency in widescreen band energy acquisition are still limited, which may limit the further advancement of practical TENG applications. In recent years, researchers have done a lot of research on improving TENG's working frequency belt.[112] As a conservative force, the magnetic force is often introduced into the TENG system as a nonlinear force to expand the bandwidth of the TENG.

In 2020, Fu et al. improved the TENG based on the cantilever beam structure, as shown in Figure 10F.[106] The bi-stable effect formed by the permanent magnet installed at the free end of the cantilever beam and fixed on the substrate expands the working bandwidth of the TENG and the bistable system has the largest frequency span compared with the monostable and tri-stable systems.

In 2022, Xu et al. proposed a wide-band triboelectric nanogenerator to collect mechanical energy in the environment, as shown in Figure 10G.[107] By adding permanent magnet components to both ends of the slider and the frame of the TENG, a nonlinear restoring force is introduced to expand the TENG resonance bandwidth, thereby increasing the bandwidth from 0.5 to 7.75 Hz. It provides a new strategy to improve the bandwidth and output performance of TENG by introducing nonlinear oscillation. And by using a non-contact structure, the energy loss caused by electrode wear and friction is avoided.

4.3 | Potential application of TENG in future electric power system

To sum up, a lot of research has been done on the magnetic energy utilization of TENG in electric power systems, and certain achievements have been achieved so far. In addition, the TENG for vibration energy acquisition, wind energy utilization, and set state detection in power systems have also achieved considerable development. Meanwhile, due to its high output voltage, it also has a wide range of potential applications in high-voltage power supply.[55,108-112] Although at present the output of the TENG, still in a lower stage is often used for sensing devices. But in terms of its development cycle, its output power has been increased from the microwatt level to the milliwatt level in only a dozen years since it was proposed. Moreover, its output performance is still improving with the efforts of a large number of researchers.[113-116] Therefore, the practical application of TENG in the future power grid will not be limited to the field of sensing devices, and its application as a direct power supply for some equipment of the power grid or power supply for wearable devices of power grid inspectors may have a very broad application prospect, which may play an irreplaceable role in the construction of new power systems.

However, there are some problems that we must pay attention to and overcome when TENG is used in the power grid.

1. Most of the equipment represented by the transmission line works outdoors, so the TENG needs to be able to overcome the impact of the natural environment, especially the impact of sun exposure, heavy rain, and dust storms on the triboelectric materials.
2. The installation location of the TENG is also one of the factors that must be considered. First of all, it is important to ensure that the installation of the TENG will not adversely affect the safe and stable operation of the electrical equipment. Taking high-voltage transmission lines as an example, we need to further consider whether the insulation requirements between the various phases of transmission lines after the installation of TENG can be met and whether the vibration amplitude of the transmission lines will be increased under the action of external forces. And on the premise of satisfying safe operation, it is necessary to ensure that the equipment is easy to install as much as possible.
3. The transmission mode of its signal also needs to be carefully considered, which not only needs to overcome the interference of the strong electromagnetic environment but also needs to match its output characteristics.

5 | CONCLUSION AND PROSPECT

This paper reviews the research progress of TENG in magnetic field utilization in recent years. It made a reasonable outlook on the possible development trend of future power grids and the prospects as well as the challenges of magnetic field energy extraction TENG in future power grids.

1. With the further adjustment of the structure and demand of the power system, the proportion of new energy power generation and the intelligence of the power grid will inevitably increase. However, the output of new energy generation is unstable, the need to cooperate with the traditional power generation form or the power system in different areas to achieve a stable power supply. The smart grid, which relies on wireless interconnection technology to achieve multi-region and multi-generation integrated control, will become the future development trend of the grid.

2. To improve the power system's intelligent monitoring, intelligent scheduling, and the ability to provide solutions in the face of unexpected situations quickly and to realize the transformation to a new type of power system, it is imperative to build a large-scale grid sensor network to collect grid operation data. Faced with the challenge of economically and efficiently powering numerous sensors, TENG stands out because of its unique advantages over traditional powering methods.

3. The constant and widely distributed magnetic energy around the transmission line is a better choice than the more random energy collected from the environment around the transmission line, such as wind, solar, and vibration energy, to power the sensors. This paper reviews the application of TENG in utilizing magnetic field and the recent research cases of powering sensing devices by collecting magnetic energy from transmission lines through TENG, showing the advantages of TENG in collecting magnetic energy from transmission lines and utilizing magnetic field, thus confirming the feasibility of powering sensing devices by collecting magnetic energy, and providing a reference for people engaged in related research fields.

4. It should be noted that it must be pointed out that although the current TENG research has achieved certain progress, the output performance has been further improved. But in general, most research is still in the laboratory stage, and the output energy is insufficient to drive the existing sensing equipment alone. In addition, it can only produce higher output under the right incentive conditions, and its adaptability needs to be significantly improved. How to further improve the output performance of the magnetic energy harvesting TENG and expand its working conditions and the corresponding energy management circuits will be the main research direction in the future. It is also the key to whether the magnetic energy collection can achieve large-scale engineering applications. It is also necessary to expand its application fields in new power systems.

In summary, due to the advantages shown by magnetic field energy extraction TENG in the power supply of electrical equipment sensors, it will have broad development potential in the future power supply of intelligent sensors in the power grid, not only to support the development of the new power grid but also to promote the further construction of the new power grid. However, it should be noted that further increasing TENG's output power and working range will be the top priority to achieve its broad prospects. Opportunities and challenges will be the central theme of the development of TENG for some time in the future.

AUTHOR CONTRIBUTIONS

Yunlong Zi, Chuanyang Li, Youping Tu, and Geng Chen: Contributed to the conception of the study and contributed significantly to the analysis and preparation of the manuscript. **Geng Chen, Chuanyang Li, and Jie Wang:** Wrote the manuscript. **Guoqiang Xu, Jingjing Fu, Abubakar Balarable Gani, Jinhong Dai, and Dong Guan:** Helped perform the analysis with constructive discussion.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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