Impedance management for accurate self-powered sensing

Jun Ma,[1] Hao Sun,[1,*] and Shuhai Liu[1,*]

[1]School of Materials and Energy, Lanzhou University, Lanzhou 730000, China

*Correspondence: liushuhai1991@live.cn (S.L.); Sun_Haoo@outlook.com (H.S.)

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Today's society relies heavily on big data, the collection of which depends on extensive sensor networks; however, powering mobile and widely distributed sensors remains a significant challenge. Self-powered sensing technology, particularly that based on triboelectric nanogenerators (TENGs)—devices that convert ambient mechanical energy into electricity—offers a promising solution by enabling sensors to operate without external power sources.[1] First proposed by ZhongLin Wang, this paradigm-shifting technology has had a broad impact on fields such as implantable medical devices, environmental monitoring, and wireless remote sensing.

Past researches have primarily focused on improving the energy harvesting performance of self-powered sensing systems based on TENGs, through material modification, device structure design, and management circuit optimization. However, less attention has been given to enhancing sensing performance—specifically, the sensing accuracy of signal monitoring—which is crucial for the effective operation of sensing systems in the fundamental level. The sensing accuracy of TENG-based systems has long been limited by two fundamental intrinsic factors. First, there exists an inherent impedance coupling between the TENG and the external sensing load, arising from the dual role of the TENG as both a power source and a sensor. This coupling effect means that variations in the sensor's impedance directly influence the output characteristics of the TENG, leading to signal distortion and inaccurate sensing results. The dynamic interaction between the internal impedance of the TENG and the external load complicates the extraction of reliable sensor signals. Second, the irregular and intermittent nature of ambient energy sources, which power the TENG, introduces instability in the electrical output. Such fluctuating energy input causes additional variability and noise in the sensor output, further degrading measurement precision. Together, these two intrinsic challenges significantly hinder the ability of TENG-based systems to achieve consistent and accurate sensing performance in practical applications.

Recent researched has developed two main strategies for impedance management to improve sensing accuracy. To address impedance coupling between the TENG and the sensor, different technical methods have been designed (Figure 1A). The first is physical decoupling, which uses a synchronous switch to physically cut off the impedance coupling.[2] The poor sensing performance of traditional strategies is due to charge loss when the triboelectric layers of a TENG approach each other. To mitigate this, a physical switch was introduced. This operates by closing to establish circuit conductivity when the TENG triboelectric layers are in contact or at their maximum separation, and opening to interrupt circuit conductivity at all intermediate positions. The research results show that as the resistance of the sensor increases, the voltage across the sensor remains constant, but the current decreases. This result confirms that the switch effectively stabilizes the voltage across the sensor and decouples it from the internal impedance of the TENG. The second method involves electrical decoupling, which can be further divided into two key approaches: energy management circuit decoupling and parallel low-resistor decoupling. An energy management circuit (EMC) effectively isolates the TENG from the sensor, which consists of a rectifier circuit, a capacitor, a diode and an LTC3588 chip. The alternating current (AC) signal output by the TENG passes through rectification, energy extraction, energy storage and voltage regulation sections in order to supply a stable direct current (DC) to power the sensors.[3] Although the EMC can convert and stabilize energy to power the sensor, the sensor is powered intermittently. Put simply, it needs to be charged for long enough to perform one cycle of switching between 'sleep' and 'work' modes. Besides, the mechanical energy irregularities in the environment cause the TENG's output performance to be unstable, which makes charging the EMC take longer. Meanwhile, the EMC itself has energy loss during the working process, further increasing the charging time. Together, these two factors cause TENG-based charging EMC to face extended charging times when driving the sensor to work, resulting in significant limitations on the sensor's ability to work in real time. As another strategy, parallel low-resistor decoupling introduces a fixed low-value resistor connected in parallel with the sensor, which helps stabilize the TENG's output voltage and mitigate impedance mismatches.[4] Consequently, changes through sensor current only reflect changes in its intrinsic resistance induced by external stimuli, thereby preserving sensing accuracy. Using this parallel configuration, a multi-modal sensing network powered directly by the TENG has been demonstrated, significantly improving sensing

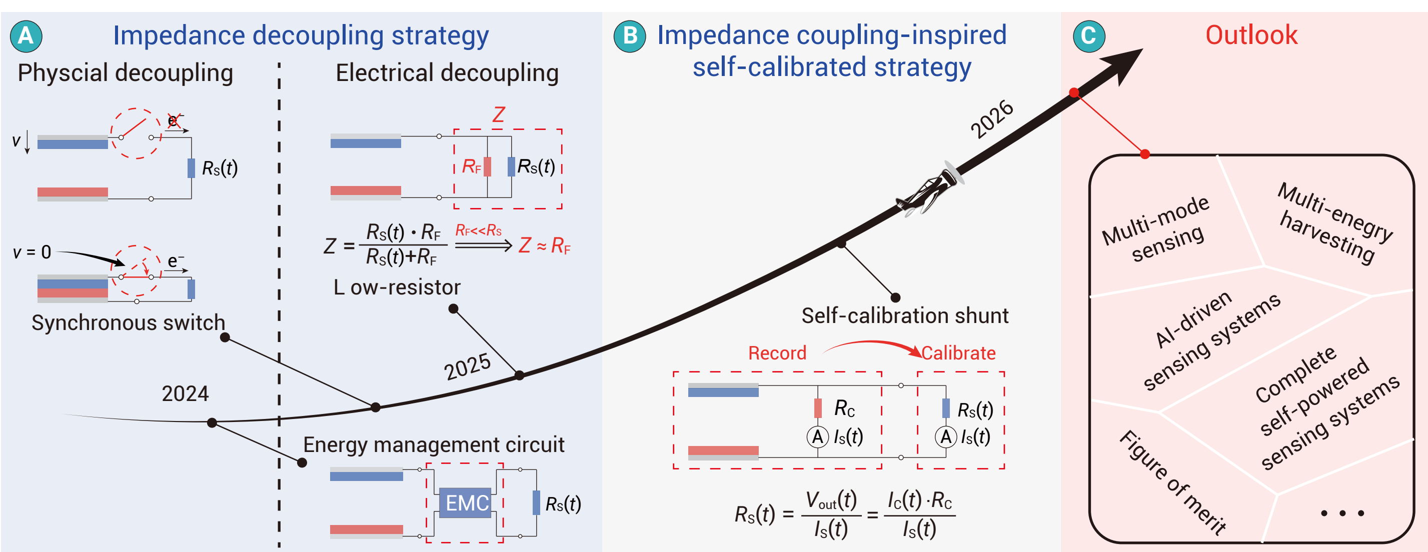

Figure 1. Roadmap toward accurate self-powered sensing via impedance management (A) Impedance decoupling strategy: physical decoupling and electrical. (B) Impedance coupling-inspired self-calibrated strategy. (C) Outlook of impedance management for accurate self-powered sensing.

stability as well as system scalability and integration potential. Despite these strategies successfully resolving the impedance mismatch issue between TENGs and sensor networks, problems still arise in self-powered sensing systems. These include a limited sensing scope and an inability to operate continuously using a single irregular environmental energy source.

While the first strategy focuses on impedance decoupling to minimize interference from impedance mismatches and achieve accurate sensing, the second strategy in turn leverages inherent impedance coupling by introducing a calibration shunt.[5] This strategy successfully eliminates the problem of increased sensor error caused by energy fluctuations when the system is powered directly by irregular environmental energy. It also fundamentally solves the impedance mismatch problem between the TENG and the sensor. This strategy can be used to create a sensing system that can effectively power temperature and relative humidity sensors, achieving a level of accuracy comparable to that of a constant voltage source. Meanwhile, the current flowing through the calibration shunt contains unique information about ambient stimuli, which can also be used to record and monitor ambient parameters. This dual functionality not only enhances sensing accuracy but also broadens the overall capabilities of the self-powered system (Figure 1B).

Despite recent advances, impedance management for self-powered sensing technology still faces five pressing challenges (Figure 1C). First, there is a need to establish standardized metrics, such as a figure of merit (FOM), that comprehensively evaluate both energies harvesting efficiency and sensing accuracy. Developing such metrics is complex because they must account for interrelated parameters including waveform characteristics, energy conversion efficiency, and impedance coupling. Current evaluations often focus on the conversion efficiency of mechanical energy without considering signal fidelity simultaneously, and this cannot represent system performance in real-world conditions. A well-defined FOM would enable systematic comparisons of TENG designs and operational environments, ultimately guiding optimization toward a balanced combination of energy harvesting and sensing capabilities.

Second, improving system endurance remains essential, as TENGs typically harvest only a single form of ambient energy, thereby limiting continuous operation under dynamic environmental conditions. For example, a sole reliance on mechanical vibrations (typically harvested by TENGs) may undermine reliability during otherwise quiescent periods. Integrating hybrid energy harvesting—combining mechanical, solar, thermal, or even biochemical sources—into a unified power supply network shows promise in sustaining sensor operation over extended periods. Early-stage demonstrations coupling TENGs with photovoltaic cells illustrate potential pathways, but challenges persist in synchronizing energy flow, managing storage, and minimizing power losses within such heterogeneous systems.

Third, achieving multi-modal sensing by integrating various sensors on a single platform can substantially expand functionality, enabling simultaneous detection of parameters such as pressure, temperature, and humidity. However, co-locating diverse sensors increases risks of signal interference, cross-talk, and data overlap. For example, triboelectric signals from mechanical events can obscure subtle temperature-induced variations unless sophisticated filtering and signal processing algorithms are employed.

Fourth, fully autonomous self-powered sensing systems have yet to be realized. Many current deployments still depend on external energy sources for data acquisition, storage, and processing tasks. Developing TENG-powered acquisition modules integrated with intelligent power management units capable of adapting to fluctuating energy availability is a critical next step.

Finally, integrating artificial intelligence (AI) into self-powered sensing presents a significant challenge: the disparity between the high-power demands of complex AI models and the limited, intermittent energy harvested from the environment. Overcoming this challenge requires the co-design of ultra-low-power computing hardware alongside energy-efficient, lightweight algorithms specifically tailored for edge inference. Advances such as neuromorphic processors and model quantization techniques have begun addressing these demands, yet significant innovation is needed to enable robust and persistent intelligent functionality directly powered by TENGs.

The shift from maximizing power output to ensuring sensing accuracy is marking a signifies a promising and noteworthy trend for triboelectric technology, positioning impedance management as a fundamental prerequisite for the reliability of self-powered system. By reconciling energy fluctuations with signal accurate and addressing critical challenges in standardization and intelligence, this evolution facilitates the realization of self-powered system capable of adaptive harvesting and precise monitoring across diverse and unpredictable environments.

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J.M. organized and wrote the paper. H.S. plotted the figure and contributed to the paper writing. S.L. conceived the idea, supervised the work, and revised the paper. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

No new data were created or analyzed in this study.