Research on efficient power management circuit for triboelectric nanogenerator (TENG)

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Abstract. In this research, we tested the electrical output characteristics under a different matching and verified the randomness of the output signal. We focused on the electrical characteristics of friction nanogenerators, analyzed the power management circuit, and then searched on the interaction of the friction nanogenerator with its power management circuit. With the use of synchronous switching technology integrated with a full-bridge rectifier and power management integrated circuit, the power conversion efficiency, especially for random discontinuous energy, was increased.

Keywords: random output signal, self-generate system, energy harvesting device, full-bridge rectifier, power management integrated circuit.

1. Introduction
The electrification process when the water droplet contacts the surface is focused on by lots of scientists [1]. Although the mechanism underlying this phenomenon is still unclear, in self-generated and energy harvester systems, this technique is well recognized as having great potential for application.

The characteristics of a discontinuous random energy harvesting system are obtained through experiments. And the three common characteristics of this kind of system are summarized. Afterward, the existing processing methods for the electrical output signal of this characteristic are analyzed, and the specific application on TENG is expounded.

Through the full bridge rectifier, the signal generated by FTENG is converted into a DC signal. Connect capacitors through PMIC for storage. Three programmable thresholds set by SET_VOUT are used to realize that the power can only be released when the stored voltage exceeds the threshold. When the voltage of the storage capacitor (VSTORE) is above 3.5V, the capacitor delivers electrical energy to the load (VOUT) [3]. When VSTORE is 2.2V, the PMIC disconnects the capacitor from VOUT. And the voltage doubler, which saves the loss of one diode's conduction voltage, was analysed in the following part.

One of the most effective techniques for collecting the random signals is called the Synchronous Switched Inductance Collection (SSHI) technique. The parallel SSHI technology has been used to flip...
the terminal voltage of PEH through an external inductor [7]. In this paper, we have conducted an analysis and research, the result shows that the conversion efficiency of random discontinuous energy can be increased without increasing the complexity of the system.

2. The TENG with High Random Output
It has been widely recognized that the character of output produced by both the power droplet-based electricity generator and triboelectric nanogenerator (TENG) has a high institute. The basic principle is based on contact-electrification, which has been documented more than 2000 years ago. In recent years, the study on physical process of contact electrification (CE) provides a systematic understanding on the characteristics of triboelectric nanogenerator (TENG) [2]. In practical engineering applications with a more complicated external environment, since droplets are not regular and periodic, the ideal data are not often accessed.

![Fig. 1](image-url) (a) The circuit device used to measure the electrical output characteristics of TENG has obtained a randomly distributed output signal through experiments. (b). Ideal data are not often accessed in application.

3. Frictional Nanogenerator Output Characteristics
The output of a typical discontinuous random energy harvesting system tends to have the following common characteristics.
1). the output voltage is an alternating current (AC) voltage
2). the output voltage has a high peak value, and the instantaneous output power is immense.
3). the output power is discontinuous and random.

3.1. AC-DC converter-full-bridge rectifier
To address the above characteristics of the energy harvester output, Yu Song, Jihong Min et al. proposed an efficient power management circuit for wireless wearable sweat biosensors at the system level in [3]. This battery-free power management circuit enables a highly stable and mass-producible battery-free wearable self-powered device by integrating it with a low-power biosensing system. The main body of the power management circuit used in this system is a commercial energy harvesting power management integrated circuit (PMIC) S6AE101A, which manages the power-level electrical signals generated by the FTENG. Looking at this set of power management circuits at the system level, as shown in Figure 1, the high-voltage AC signal generated by the FTENG is first converted by a full-bridge rectifier to a DC signal, which is stored in two parallel-connected capacitors (220 and 22F) via the PMIC. The programmable threshold value set by three SET_VOUT is used to achieve that the power can be released only when the stored voltage exceeds the threshold value. When the storage capacitor’s voltage (VSTORE) reaches 3.5V, the capacitor delivers electrical energy to the load (VOUT). When VSTORE drops to 2.2V, the PMIC disconnects the capacitor from VOUT until VSTORE is recharged. This method enables power management for self-powered wearable devices by integrating with a low-power biosensing module.
3.2. A study of voltage multiplier.

The AC-DC converter-full-bridge rectifier described above is one of the most classic ways to convert an AC signal to DC for FTENG. Another common AC-DC converter circuit is the voltage multiplier. In Figure 2a, the power management circuit consists of two diodes and a capacitor C. At each moment, only one diode in the voltage doubler is on, so the circuit can only output half the energy of the alternating current. However, compared to a full-bridge rectifier, the voltage doubler saves the loss of one diode's conduction voltage at each moment. Therefore, whether the rectifier circuit uses a voltage doubler or a full-bridge rectifier needs to be decided according to the output characteristics of the energy harvesting device.

Since the output characteristics of the friction nanogenerator are high voltage and low current, the peak output voltage can reach tens or even hundreds of ohms, which can completely ignore the diode conduction voltage. The energy loss caused by the conduction voltage landing on the diode is much lower than the loss caused by the voltage doubler consuming half a cycle of electrical energy, so the full-bridge rectifier is usually used for the power management of the friction nanogenerator to improve the conversion efficiency of electrical energy.

William Harmon et al. have proposed a power management circuit that does not require a power supply other than the TENG device and an integrated circuit to convert the TENG pulsed output to a stable voltage. [4] In this power management system, the power management circuit consists of only discrete semiconductor devices and inductors. This study presents a self-driven power management solution for self-powered systems without the need for additional power supplies.

However, since there is always an equivalent capacitance Ce in the equivalent circuit model of most energy harvesting devices, including friction nanogenerators, the TENG operates with the longitudinal motion of the electrodes, and the electric capacity of the TENG changes due to the change of the electrode distance, which generates a current in the external circuit. The internal circuit of the TENG can be equivalently simulated by a variable capacitor and variable resistance with a DC power supply [5], as shown in Figure 2b. Niu and Wang in 2015 developed an alternative equivalent circuit model for the TENG, as shown in Figure 2c, in which the TENG is modeled as a series connection of a capacitor and a voltage source, both of which vary in characteristics according to the structure of the TENG.
These two circuit models allow us to analyze the interaction of the friction nanogenerator with its power management circuit. [6] The charging and discharging of this equivalent capacitor consumes a vast amount of electrical power for the energy harvesting device, so the integration of an asynchronous switching harvesting inductor (SSHI) on top of the rectifier circuit can increase the power conversion efficiency of the energy harvesting and power management circuit by more than 80% [7].

4. Improved power conversion efficiency through integrated switching circuits
The parallel SSHI circuit is shown in Figure 3. It works by closing switch S when the power output from the energy harvesting device to the power management circuit reaches a minimum value, forming an oscillating circuit of $C_e$ and $L$.

At the moment of one-half of the LC oscillation cycle, the voltage in $C_e$ reverses to reach the peak value of the voltage, at which time the switch S is closed. The addition of the LC oscillator changes the voltage polarity of $C_e$ so that the voltage of the energy harvesting device reverses rapidly, and therefore
reduces the power consumed when Ce is charged and discharged. According to the oscillation period of the LC oscillator, the conduction time t of S can be expressed as in [8].

\[ t = \pi \sqrt{LCe} \]

The physical specificity of friction nanogenerators dictates that the electrical output of friction nanogenerators is still AC although it has a high peak voltage and a low current. So when processing them through the power management circuitry it is possible to follow the same approach as for discontinuous random energy harvesters, since the output of most energy harvesters has an AC character.

Figure 5. (a). Frictional nanogenerator output image with very high peak voltage and AC output [9], (b). Piezoelectric energy harvester output and friction nanogenerator output via SSHI circuit

The most current application of SSHI technology is the study of piezoelectric energy harvesters and their power management circuits. The output of a piezoelectric energy harvester is closer to a sinusoidal waveform than the output of a friction nanogenerator, with smaller peak voltages and higher currents, so SSHI technology has been used first here.

5. Conclusion

By proposing an efficient power management circuit with synchronous switching technology integrated with a full-bridge rectifier and a power management integrated circuit at the system level, the conversion efficiency of random discontinuous energy can be increased without increasing the complexity of the system and the loss of electrical power in the components. The ideas and analysis methods proposed in this paper for the integration of synchronous switching technology with full-bridge rectifiers and PMICs can also be used in other discontinuous random energy harvesting systems.

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