論 文 の 内 容 の 要 旨

論文題目

Development of Nonlinear Interface Circuits for Electret Kinetic Energy Harvester

（力学的エレクトレット環境発電器のための非線形電源管理回路の開発）

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In the scenario of the Internet of Things (IoT), wireless sensor nodes play a fundamental role for sensing and communication. Currently, most nodes are battery-powered. However, with the proliferation of sensor nodes, the choice of battery becomes unfavorable considering its inevitable maintenance and environmental burden. On the other hand, energy harvesting, which exploits ambient energy to generate electricity, has emerged a promising alternative solution in place of batteries. So far, the main task for small-scale energy harvesting is to enhance the output power to support a wider range of low-power electronics.

This thesis focuses on electret-based in-plane kinetic energy harvester which has been demonstrated to be MEMS compatible, low in profile and to harvest more power in sub-100 Hz frequency range compared electromagnetic counterparts. However, its output power is severely constrained by the shunting effect of parasitic capacitance due to its lower internal capacitance. Structural designs have been attempted to reduce the parasitic capacitance. On the other hand, the shunting effect can be compensated by nonlinear power management circuits such as SSHI (Synchronous Switch Harvesting on Inductor). However, as electret-based energy harvester exhibits low output current and low internal capacitance, high-voltage small-signal components should be selected to minimize introduced capacitance and leakage current. Therefore, there has been no existing study focusing on nonlinear circuits for electret-based energy harvester. The present study attempts to develop nonlinear circuits for electret-based energy harvester, aiming at enhancing its output power. The objective of the present study is to present new approaches to optimize energy conversion from kinetic energy (human motion) using rotational electret energy harvester and to describe the most important parameters in circuit design. Meanwhile, in terms of wearable application, the height of the proposed circuit matters, because the height of nonlinear circuits, if composed of discreet components, sometimes exceeds that of the electret energy harvester itself, which makes the proposed circuit less attractive. Therefore, the applicability of the proposed circuits to integrated circuit (IC) technology is also to be investigated in the present study, aiming at realizing a practically-attractive low-profile circuit.

In the present study, the electromechanical transduction mechanism of electret in-plane energy harvester is elucidated analytically for the first time, which confirms the applicability of nonlinear circuits on electret kinetic energy harvester. The proposed model also enables a comparison of output characteristics between electret-based and piezoelectric energy harvester, which specifies challenges of nonlinear circuits on electret-based energy harvesters, which are much more susceptible to parasitic capacitance than piezoelectric ones.

Development of SSHI for electret-based rotational energy harvester is presented in the present study. The theoretical performance of SSHI on electret EH is derived and verified by simulation with LTspice, showing a power enhancing ratio of 6.7 against the standard case, where a conventional full-bridge rectifier is employed. Circuit design of parallel SSHI is then proposed using a resistive voltage divider as the low-voltage signal generator. Based on this voltage-divider SSHI design, experimental validation based on a test bench of electret-based energy harvester is carried out using discrete components. In the external-powered SSHI where the control block is powered by external DC supply, a power enhancing ratio of 2.47 is experimentally achieved at a rotating speed of 1 rps. In addition, simulated results are in accordance with experimental results, which makes it possible to analyze SSHI circuit based on simulation. As a result, the inversion ratio, which is the benchmark of SSHI performance, is highly related to the parallel resistance of the inductor due to the low shunt capacitance of electret energy harvester. Since the serial resistance of the inductor is not important in determining SSHI performance, it is valid to utilize thinner wires for reducing the height of the inductor, which dominates the height of the whole circuit. According to the circuit efficiency analysis, the voltage-divider and the diodes in rectifier turned out to be quite lossy in the high voltage range where the performance of SSHI increases. Consequently, the efficiency of SSHI drops from over 80% @ 30V to below 30% @ 200V.

In this regard, a novel dual-stage electrode design is proposed to achieve efficient operation of SSHI. The proposed dual-stage electrode aims to reduce power loss by removing the lossy voltage divider. Instead of voltage-divider, a minority of area in the stator serves as a control stage to provide low-voltage signal to the control block; whilst a power stage with major area is in charge of power generation. Thanks to this isolated control stage, the switch action is also immune to voltage drops led by subsequent converter operation. Consequently, a power enhancing ratio of 4 is achieved, which is 1.56 times of power harvested with the voltage-divider SSHI. The efficiency of SSHI is thus enhanced. Self-powered SSHI is then examined with a dual-polarity converter to supply the control block, making the system energetically closed. In addition, dual-stage SSHI is also successfully implemented on a fully-integrated electret EH instead of test bench, with cold-start and self-powering ability confirmed under random excitation. However, the power enhancing ratio reduces to 1.4 in the self-powered SSHI with an overall efficiency of 25%, due to the low voltage rating and low efficiency of the dual-polarity converter.

Since the proposed parallel SSHI suffers from the low efficiency of dual-polarity rectifier and requires high voltage (input voltage>200V) DC/DC converter, which is difficult to realize efficiently, a novel dual-stage SECE (Synchronous Electric Charge Extraction) circuit for electret-based energy harvesters is presented. Compared with SSHI, SECE is free of dual-polarity rectifier, and is expected to harvest more power in lower load voltage range. Therefore, a higher overall power enhancing performance is expected with SECE. First, the theoretical performance of SECE on electret EH is derived and then verified by simulation with LTspice. Circuit design of SECE is then proposed, featuring a novel switch control scheme which is adaptive to arbitrary internal capacitance and the external inductor. Test-bench-based experimental validation is carried out with a control block externally powered. Consequently, a power enhancing ratio of 2.77 against full-bridge rectifier is experimentally achieved at a rotating speed of 1 rps. Based on the simulation, the end to end efficiency of the proposed SECE circuit reaches 80% at a DC load voltage of 10V, which is superior to that in SSHI. Meanwhile, the voltage stress at generator output in SECE is also several times lower than that in SSHI, making SECE friendlier to IC technology. Self-powering and cold-start of the proposed SECE can be achieved by utilizing the charges accumulated in control stage. Based on simulation, the inductor in SECE could be lower than 100 μH without severely reducing the power enhancing performance, which is in favor of the circuit miniaturization. Based on the efficiency analysis, reducing the forward voltage drop of the freewheel diode is crucial to improve the SECE performance in low load voltage range.

The IC-compatibility of the proposed circuits is investigated. It is found that except the inductor, components in the proposed nonlinear circuits can be integrated on chip by utilizing high-voltage BCD process. The inductor, on the other hand, could be tailored to be low-profile in our case according to the discussion above. With the aid of IC technology, the power consumption of the control blocks in nonlinear circuits should be further reduced. In this regard, tri-stage SSHI circuit is proposed to remove the low-efficiency dual-polarity converter. Instead, the control block is powered by a third stage which outputs dual-polarity voltage with limited power. In this way, the converter in the power stage could be a classic unipolarity converter which exhibits higher efficiency. For SECE, with reduced power consumption of control block using IC, it becomes feasible to power the control block by the DC-side storage capacitor of the control stage, thereby achieving self-powering and cold-start. Therefore, low-profile nonlinear circuits is achievable for electret energy harvester with the aid of IC technology.

To summarize, the present study presents the development of nonlinear circuits (SSHI, SECE) for electret kinetic energy harvester for the first time. Detailed circuit design of the nonlinear circuits is then proposed, simulated and experimentally validated. SSHI is developed for its higher achievable output power at generated output over SECE, but it needs high-voltage DC/DC converter which currently suffers from low efficiency and low voltage rating. In this regard, SECE is developed for its higher output power at low-voltage DC load over current SSHI. A novel dual-stage electrode design is proposed to address the high output voltage of the electret energy harvester, thereby enabling efficient operation of SSHI and innovative design of control block in SECE. Consequently, the effectiveness of nonlinear circuits is experimentally confirmed. In regard to battery-less operation of the circuits, self-powering and cold-start schemes for nonlinear circuits are proposed. The ability of cold-start and self-powering under random excitation is experimentally confirmed for the proposed dual-stage SSHI. Circuit analysis based on simulation is carried out to provide guidance for improving the performance of the proposed nonlinear circuits and for selecting the inductor which usually dominates the height of the circuit. Based on the efficiency analysis, the lossy components in the proposed circuits are located and methods to reduce their power consumption are indicated. By analyzing how the inductance, series resistance and parallel resistance of the inductor influence the power enhancing performance, it is found that the inductor in both circuits could be scaling down to be low profile, without severely destroying the power enhancing performance. It is also found that except the inductor, components in the proposed nonlinear circuits can be integrated on chip by utilizing high-voltage IC process. The inductor, on the other hand, could be tailored to be low-profile in our case. Therefore, low-profile nonlinear circuits for wearable application is feasible for electret energy harvester.