International Journal of Mechatronics, Electrical and Computer Technology (IJMEC)
ISSN: 2305-0543 (Online), ISSN: 2411-6173 (Print)
Vol. 12 (46), Oct. 2022, pp. 5297-5300

Implementation of Wearable Thermal Energy Harvesting System with Conductive Thread

Mostafa Noohi
Department of Electrical Engineering
Yazd University
Yazd, Iran
m.noohi75@yahoo.com
Tel Number: +98-917-4140688

Ali Mirvakili
Department of electrical engineering
Yazd University
Yazd, Iran
ali.mirvakili@yazd.ac.ir
Tel Number: +98-35-31232369

***Abstract*—Energy harvesting is a promising solution for powering the portable electronic devices. Energy of the environment or energy from the human body can be extracted using various techniques. In addition, the growth of personal health care systems demand the advancement of wearable electronics. Accordingly, implementation of wearable devices powered by energy harvesting is of interest. In this paper, a practical, economical, and flexible approach based on the conductive printing technology on the fabric for such implementation is proposed. A conducting thread as a technique for transmitting power to a wearable energy harvesting device is introduced. In this manner, the thermal energy of the human body is converted into electrical energy by a thermoelectric generator; then, through a fabric on which conductive printing or thread is used, will be transferred to the electronics of a wearable device. As the incoming voltage from the heat of body is low in amplitude, a boost converter is used to increase the voltage level. Conductive printing technology on fabric substrate has a variety of applications, and with a particular focus on energy extraction systems can be introduced to wireless body area networks. In this paper, the implemented system based on thread as a conductive path can provide output voltage of 5 V with the efficiency of 23%.**

Keywords— Conductive thread; energy harvesting; inkjet printer; thermoelectric; wearable device.

I. INTRODUCTION

Energy harvesting (EH) techniques are used to extract energy from the environment or human body and convert it into electrical energy on a small scale. Energy sources which can be used in this manner include heat, solar, mechanical (kinetic), radio waves, to name a few [1]. Many wireless sensor networks (WSNs), which are used for remote control and monitoring, are powered by batteries. Batteries require maintenance, replacement and recharging costs due to their limited lifespan; they are also harmful to the environment [2]. EH techniques have emerged as a promising solution to meet the demand for power supply for various autonomous devices and are an efficient option for battery replacement [3]. One of the available and valuable resources is the heat energy of the human body [4]. This heat energy can be converted into electrical energy through a thermoelectric generator (TEG). Therefore, extracting energy from the body would be a practical solution by the means of TEGs. In this regard, the operation of the battery-free low power and portable systems would be realized.

Due to the wide spread use of WSNs in near future, the personal health care systems can be monitored by the wireless body area networks (WBANs). They are commonly used to not only measure the body's vital signs, but also to identify and diagnose diseases. This system helps people to control, monitor and prevent diseases in normal and abnormal conditions [5]. One of the most suitable places to install TEGs in the portable EH system is in clothing which is referred to as a wearable device or system [5]. In this scenario wire/copper track typically is used to transfer electrical energy to a low-power electronic device. This is unpleasant and annoying in many cases. WBANs can be placed on the human body, or it can be implanted inside the body. Wearable WBAN systems are a convenient solution for portable medical applications [6]. In order to provide the conductive path, the inkjet printing technology can be utilized which has emerged in many applications, including EH techniques [7]. In addition, conductive threads can be provided to make a conductive path in a wearable equipment [8]. In [9], the steps of manufacturing circuits and organic thin film transistor (OTFT) using inkjet printing are introduced. In [10] the first MEMS switch was made using inkjet printing by the University of California. In [11], a small and inexpensive antenna has been implemented in the frequency band of 4.79 to 5.04 GHz using inkjet printing. In addition, in [12], using this technology, the authors have succeeded in printing their ink on clothes. In [13] a method is reported by which energy is extracted from mechanical vibration. The principles of this work have been proved by using a laboratory-made sample with inkjet printing technology. The other approach is using the conductive thread for providing the connection to be used in WBANs. In [14], planar inverted-F antennas (PIFAs) woven with conductive textiles and embroidered patterns with conductive threads have been studied. In [15], integrated rectangular arrays make flexible and lightweight fabric using conductive thread to power wearable electronic devices. In [16] a flexible, fully stretchable radio frequency coil is introduced which can be used for magnetic resonance imaging. In this method, silver conductive coating on a stretchable fabric is used.

In this article, the aim is to implement and build a thermal energy extraction system from the human body as a wearable product. For this purpose, we have considered two ideas of inkjet printing and conductive thread so that we can realize and implement wireless energy transmission. The work is done using conductive embroidered thread on the fabric. The

Article History:
Received Date: May.17, 2022, Accepted Date: Jul. 15, 2022, Available Online: Oct. 01, 2022

rest of paper is as follows. Sections II describes the energy harvesting system. Power transmission is explained in section III. Experimental results are given in section IV. Finally, section V concludes the paper.

II. Energy harvesting system

A. Thermoelectric generator

The TEG is used to extract heat energy from the human body and convert it into electrical energy. TEG is a semiconductor element composed of a number of P and N type semiconductors. With the Seebeck effect, this element converts the temperature difference into an electrical potential difference [17]. A TEG device work on this principle that the greater the temperature difference between the hot and cold sides, the greater the received power. For this purpose, a small heatsink in the cold part is installed in order to help increasing the temperature difference. It is worth mentioning that the series and parallel connection of TEGs can be implemented to increase the voltage level and output current. Due to the internal structure of TEGs, which consist of a number of thermocouples, the open circuit voltage of a TEG, consisting of *n* thermocouples connected in series and in parallel with the thermal connection, is expressed as (1),

$$V_{oc} = S \times \Delta T_{TEG} = n \times \alpha (T_{HJ} - T_{CJ}) \quad (1)$$

where α and *S* represent the Seebeck's coefficient of a thermocouple and a TEG, respectively, ΔT_{TEG} is the temperature difference, T_{HJ} and T_{CJ} are the temperatures of the hot and cold side, respectively. Moreover, the output power of the TEG can be calculated as (2),

$$P_{TEG} = \frac{\alpha^2 . \Delta T_{TEG}^2 . R_L}{(R_{TEG} + R_L)^2} \quad (2)$$

where R_{TEG} is the TEG internal resistance, and R_L is the load resistance [18]. The maximum power transfer from the TEG source to the load is obtained under the condition of $R_{TEG}=R_L$.

B. Boost converter

In the thermal EH system from the human body, the use of a boost converter is necessary since the direct voltage drawn from the TEG is very low. Accordingly, a boost converter is required to achieve the desired voltage level. The chip used in this paper as the boost converter is LTC3108. This chip is a highly integrated DC-DC converter ideal for harvesting and managing surplus energy from extremely low input voltage sources such as TEGs, thermopiles and small solar cells. The topology implemented in this chip can be operated from input voltages as low as 20 mV. Indeed, placement of an external step-up transformer is considered for the chip to be able to work for the low incoming voltages in the order of 20 mV. In this manner, the turns ratio of this external transformer plays a key role in determining how low the input voltage can be for the converter to start. Using a 1:100 turn ratio, the start-up voltages as low as 20mV can be yielded. In LTC3108 a resonant step-up oscillator is formed with the combination of a small coupling capacitor together with an external step-up transformer and a MOSFET switch. This also allows this chip to provide multiple regulated output voltages for supplying other low power electronics. The induction of the secondary winding determines the resonant frequency of the oscillator according to (3), where L_{sec} is the inductance of the secondary winding of transformer, and *C* is the load capacitance on the secondary winding.

$$Frequency = \frac{1}{2.\pi.\sqrt{L_{\sec}.C}} \quad (3)$$

The boost converter is capable of producing a larger output DC voltage than the input DC value [19]. In a DC-DC converter, the voltage conversion, M(D), is the ratio of the output to its input voltage, which depends heavily on the value of the duty cycle (D) of pulse width modulation (PWM) signal applied to the main switch of the converter. For an ideal boost converter, the voltage conversion can be calculated as (4). In practice, due to the presence of non-ideal components, the maximum value that the output voltage of the boost converter can provide will be somewhat limited, which depends upon the efficiency of converter.

$$M(D) = \frac{V_{out}}{V_{in}} = \frac{1}{D'} = \frac{1}{1-D} \quad (4)$$

In general, by tuning the duty cycle, any desired output voltage can be achieved. However, due to the variations in the load or incoming voltages, a control mechanism should be added to stabilize the output voltage which can be implemented based on the negative feedback concept. It is worth noting that this chip is capable of operating from a TEG with the temperature difference as low as 1°C. This, indeed, makes this chip a perfect choice for harvesting energy of human body in terms of wearable electronics.

As mentioned in the previous subsection, the maximum power transfer is possible, provided that the load and the source have equal values. Based on the datasheet of this chip, the internal resistance (ESR) of most TEGs is in the order of 1-5Ω. In addition, this LTC3108 chip depending upon the turns ratio of the transformer as well as incoming voltage provides the input resistance in the range of 2-10Ω. Due to the fact that this chip behaves as the load of the TEG, the optimum power transfer can be utilized. The efficiency of the converter based on the datasheet of this chip, varies according to the incoming voltage and based on the turns ratio of the transformer. For the ratio of 1:100, the efficiency varies from 10-40% with input voltage range of 50-250 mV.

III. Power transmission

In this paper, we want to transfer the electrical power generated from body heat through a conductive substrate that is placed on the fabric. This conductive substrate can be based on inkjet printing or conductive thread.

A. Conductive thread

Recently, wearable and textile devices have received attention in a variety of fields, including medicine, healthcare, mobile communications, and military programs [20]. In this paper, according to Fig. 1, a fabric embroidered with conductive thread is used as a substrate to conduct electrical energy obtained from body heat. This technology has advantages such as flexibility, low cost, lightness and easy integration in clothing.

IEEE Office - SEET Complex, Federal University of Technology, Owerri, Nigeria, https://aeuso.org
EISSN: 2305-0543, PISSN: 2411-6173

Fig. 1. Embroidered fabric with conductive thread.

Conductive shapes can be designed with circuit simulation software and then converted to the corresponding CAD models. CAD models are then entered into an embroidery software, through which the movement of embroidery needles is determined. This pattern is then applied to the automatic embroidery machine [15].

B. Inkjet printing

Another technology used in this manner is inkjet printing to create electrical conductivity. Commercially conductive inks on the market are often composed of the noble metals of synthesized nanoparticles such as copper, gold or platinum. These nanoparticles are well dispersed and stabilized in a mixture of solvents [21]. The ink of silver nanoparticles is composed of silver and solvent nanoparticles that hold the nanoparticles as ink. The average grain size of silver nanoparticles varies from 10-150 nm [7]. A sintering process is usually followed immediately after the inkjet printing of the desired pattern. Baking is necessary to increase the conductivity of printed patterns. Therefore, higher conductivity can be achieved when silver nanoparticles are fired at higher temperatures [7].

IV. Experimental Results

In this article, a TEG with the part number of SP1848-27145 is used along with a heatsink. Depending on the need, we can produce higher voltage levels with placing a higher number of series connected TEGs. The specifications obtained from the aforementioned TEG are listed in Table I. The open circuit output voltage and short circuit output current are reported in this table. As mentioned earlier, and it is evident from the results of this table, to get higher voltage or current, a larger number of TEGs should be utilized.

TABLE I. Specifications of TEG.

Temperature Differential (°C)	**2**	**3**	**4**	**5**	**6**
Open Circuit Output Voltage (V)	0.098	0.140	0.176	0.230	0.268
Short Circuit Output Current (mA)	11.3	22.4	28.8	47.2	55.7

The amount of power received from TEGs are depicted in Fig. 2. This figure shows the power received from one or two TEGs in series. Based on this result, by placing two TEGs in series connection, a higher output power is received. Moreover, the output power will increase with temperature difference.

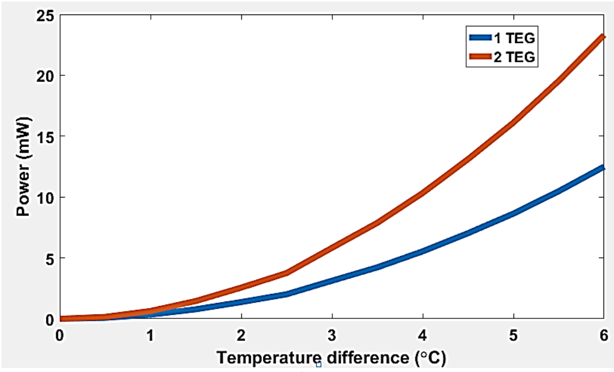

Fig. 2. Power input from one to two TEGs.

The schematic of the proposed circuit based on the boost converter is shown in Fig. 3. The voltage received from a TEG enters a step-up transformer, T1, which is controlled via the SW pin of the LTC3108. This chip by detecting the output of the transformer perform the switching operation, and the output voltage around 5V would be generated at its output, with the efficiency of 23% according to the efficiency curve provided in the datasheet.

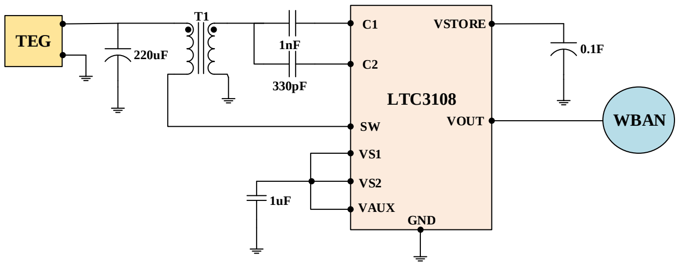

Fig. 3. Schematic of boost converter for thermal EH.

The LTC3108 chip output can be used to set up a wearable WBAN system. The final circuit of EH based on the extraction of heat from the human body is illustrated in Fig. 4, which is used to transfer electrical energy from the conductive thread embroidered on the fabric. This fabric represent a wearable dress. Due to the special feature of LTC chip, which does not require any external power supply and feeds only on the energy harvested, it is also a practical approach for making any portable and wearable WBAN devices.

IEEE Office - SEET Complex, Federal University of Technology, Owerri, Nigeria, https://aeuso.org
EISSN: 2305-0543, PISSN: 2411-6173

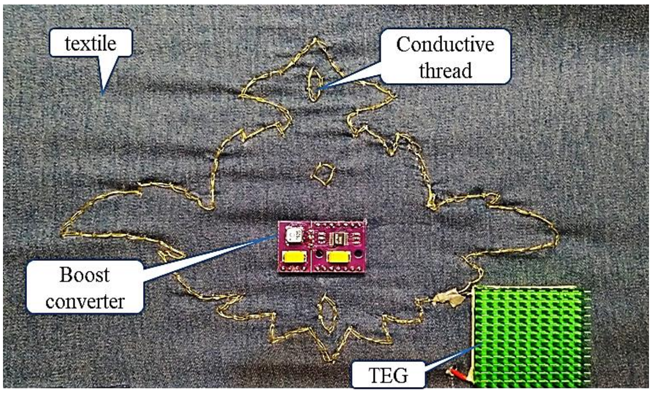

Fig. 4. Complete thermal EH circuit with conductive thread.

V. Conclusion

In this paper, an EH system that can convert body heat into electrical energy is implemented. Also, instead of using usual copper wires that are annoying for the user, to transfer this electrical energy, inkjet printing or conductive thread technology can be used on the fabric. Here, we have used the embroidered conductive thread as a means to provide the connections, and LTC3108 is used for harvesting the heat energy of human body. Due to the fact that this system does not require any external power supply and due to the presence of conductive yarn or inkjet printing, it is considered as a wearable device and can be offered as a wearable WBAN product. The output voltage of the boost converter used is equal to 5 volts and the efficiency is 23%.

References

[1] Y. Kheng Tan, Energy Harvesting Autonomous Sensor Systems Design, Analysis, and Practical Implementation, CRC Press, 2013.

[2] Y. Wu, Z. Yang, F. Lin and W. Xu, "Towards Batteryfree and Wireless Sensing for Personalized Ultraviolet Exposure Monitoring," *IEEE Sensors Journal*, vol. 18, no. 13, pp. 5515-5521, July1, 2018.

[3] S. C. Chandrarathna and J.-W. Lee, "A dual-stage boost converter using two-dimensional adaptive input-sampling MPPT for thermoelectric energy harvesting," *IEEE Transactions on Circuits and Systems I: Regular Papers,* vol. 66, no. 12, pp. 4888-4900, 2019.

[4] H.-P. Wong and Z. Dahari, "Human body parts heat energy harvesting using thermoelectric module," in *2015 IEEE Conference on Energy Conversion (CENCON)*, 2015: IEEE, pp. 211-214.

[5] S. M. Demir, F. Al-Turjman, and A. Muhtaroğlu, "Energy scavenging methods for WBAN applications: A review," *IEEE Sensors Journal,* vol. 18, no. 16, pp. 6477-6488, 2018.

[6] A. Pantelopoulos and N. G. Bourbakis, "A survey on wearable sensor-based systems for health monitoring and prognosis," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews),* vol. 40, no. 1, pp. 1-12, 2009.

[7] S. Kim, R. Vyas, A. Georgiadis, A. Collado, and M. M. Tentzeris, "Inkjet-printed RF energy harvesting and wireless power trasmission devices on paper substrate," in *2013 European Microwave Conference*, 2013.

[8] B. Ivsic, D. Bonefacic, and J. Bartolic, "Considerations on embroidered textile antennas for wearable applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 12, pp. 1708-1711, 2013.

[9] E. Ramon, C. Martínez-Domingo, A. Alcalde-Aragonés, and J. Carrabina, "Development of a simple manufacturing process for all-inkjet printed organic thin film transistors and circuits," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems,* vol. 7, no. 1, pp. 161-170, 2016.

[10] E. S. Park, Y. Chen, T.-J. K. Liu, and V. Subramanian, "Inkjet-printed micro-electro-mechanical switches," in *2011 International Electron Devices Meeting*, 2011.

[11] W. T. Li, Y. Q. Hei, P. M. Grubb, X.-W. Shi, and R. T. Chen, "Inkjet printing of wideband stacked microstrip patch array antenna on ultrathin flexible substrates," *IEEE Transactions on Components, Packaging and Manufacturing Technology,* vol. 8, no. 9, pp. 1695-1701, 2018.

[12] W. G. Whittow *et al.*, "Inkjet-printed microstrip patch antennas realized on textile for wearable applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 13, pp. 71-74, 2014.

[13] B. Ando, S. Baglio, A. R. Bulsara, V. Marletta, V. Ferrari, and M. Ferrari, "A low-cost snap-through-buckling inkjet-printed device for vibrational energy harvesting," *IEEE Sensors Journal,* vol. 15, no. 6, pp. 3209-3220, 2014.

[14] B. Ivsic, D. Bonefacic, and J. Bartolic, "Considerations on embroidered textile antennas for wearable applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 12, pp. 1708-1711, 2013.

[15] D. Vital, S. Bhardwaj, and J. L. Volakis, "Textile-based large area RF-power harvesting system for wearable applications," *IEEE Transactions on Antennas and Propagation,* vol. 68, no. 3, pp. 2323-2331, 2019.

[16] J. M. Vincent and J. V. Rispoli, "Conductive thread-based stretchable and flexible radiofrequency coils for magnetic resonance imaging," *IEEE Transactions on Biomedical Engineering,* vol. 67, no. 8, pp. 2187-2193, 2019.

[17] M. O. Cernaianu, C. Cirstea, and A. Gontean, "Thermoelectrical energy harvesting system: Modelling, simulation and implementation," in *2012 10th International Symposium on Electronics and Telecommunications*, 2012.

[18] Y. K. Tan, *Energy Harvesting Autonomous Sensor Systems: Design, Analysis, and Practical Implementation*. CRC Press, 2013.

[19] R. W. Erickson and D. Maksimovic, *Fundamentals of power electronics.* Springer Science & Business Media, 2007.

[20] H. Lee, J. Tak, and J. Choi, "Wearable antenna integrated into military berets for indoor/outdoor positioning system," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, pp. 1919-1922, 2017.

[21] D. Godlinski, R. Zichner, V. Zöllmer, and R. R. Baumann, "Printing technologies for the manufacturing of passive microwave components: antennas," *IET Microwaves, Antennas & Propagation,* vol. 11, no. 14, pp. 2010-2015, 2017.

IEEE Office - SEET Complex, Federal University of Technology, Owerri, Nigeria, https://aeuso.org
EISSN: 2305-0543, PISSN: 2411-6173