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Thermal Energy Based Resonant Inductively Coupled Wireless Energization Method for Implantable Biomedical Sensor

Biswaranjan Swain, Durga P. Kar, Praveen P. Nayak, and Satyanarayan Bhuyan*

Abstract—In order to energize the biomedical implantable electronic devices wirelessly for in vivo health monitoring of patients in remote and inaccessible areas, an alternate driving energy source is highly desirable and increasingly important. In pertinent to this, a thermal energy driven resonant inductively coupled wireless energizing scheme has been developed for powering biomedical implantable devices. The system is designed to convert the generated heat energy to a high frequency energy source so as to facilitate energy transfer through resonant inductive link to the automated biomedical sensing system allied with the receiver unit. The automated biomedical smart sensor is competent to acquire the body parameter and transmit the consequent telemetry data from the body to the data recording segment. The real-time body temperature parameter in different conditions has been experimented. To ensure its accuracy, the sensed data have been matched with the observations carried out by a calibrated device. The intended scheme can be utilized for wireless monitoring of other health parameters like physiological signals and bladder as well as blood pressure of the patients.

1. INTRODUCTION

Biomedical implantable electronic devices have been considered as an imperative segment to facilitate the health observation, diagnosis, and therapeutic in modern medicines for patients [1–5]. Nonetheless, intelligent biomedical implantable sensors are vital for decisively sick patients for spontaneous remote patient monitoring with accurate & continuous health observation to boost the quality of care and patient autonomy. By and large, those implantable sensors are electrified/energized either through external wired power supply to the implant internal circuits or by batteries kept inside the implantable device [6–10]. Although this usual energizing method has a high potential for powering the implantable devices but there are ubiquitous difficulties and cumbersome effect during their action. There is a threat in snapping of wire allied with the implants and external power supply through the body. The patients also have to suffer for replacement of corroded batteries embedded inside the implants undergoing repeated surgery. The embedded battery size may also refrain the miniaturization of the implantable electronics circuit. The difficulties linked with the presently available excitation/energizing system necessitate the pursuit of resonant inductive link based wireless powering system for implantable devices which is cordless, reliable, safer, smarter, environmental friendly and suitable for animal body [11–14]. To expand the usability of the wirelessly energized implantable electronic devices for continuous patient monitoring in inaccessible and outdoor areas derelict of grid power supply, harvested thermal energy based energizing system can be a partial and accepted solution [15–18]. Thus, an alternate viable approach in the form of thermal energy based resonant wireless energizing system has been proposed for implantable biomedical electronic sensor. The proposed technique enables the transformation of heat energy to high frequency ac signal which is highly required for the drive of resonant inductive link allied with the automated wireless biomedical sensing system.

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* Corresponding author: Satyanarayan Bhuyan (satyanarayanbhuyan@soa.ac.in).
The authors are with the Department of Electronics and Communication Engineering, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar 751030, India.

2. SYSTEM ARCHITECTURE AND EXPERIMENTAL DESIGN

The system architecture of thermal energy driven resonant wireless power transfer system for implantable electronic sensor is schematically illustrated in Fig. 1. The intended health observation process involves two main sections such as harvested thermal energy driven resonant inductively coupled wireless power transfer system and the implantable smart sensing section. In the proposed method, a thermoelectric generator (TEG) module is used to generate the voltage by harvesting the available abundant heat energy for charging the super capacitor. The thermoelectric generator comprises of TE modules that are kept between two thermal energy transfer system (a heat sink and a hot side heat exchanger). The TE module consists of two ceramic substrates in which many pairs of bismuth telluride dice (Bi_2Te_3) are sandwiched that is typically used to convert the thermal flux to electrical energy in the form of voltage due to seebeck effect. The low magnitude voltage is further strengthened and got its maximum power point tracking (MPTT) through a boost converter integrated with LTC3108. With a temperature difference of 100°C a voltage ranging from 20 mV to 1.5 V has been acquired and further boost up to 5 V. In addition to this, a step up transformer along with LTC3108 offers a full power management solution for wireless powering as well as data acquisition. An uninterruptible power source would be accessible by a super capacitor which is used for power storage under on condition and provides power when the input voltage source is unavailable. To produce the power with constant amplitude, a boost converter is allied with the battery as the input source. The TEG generated voltage is further intensified by the boost converter with suitable switching frequency. The boost converter with a filter inductor and capacitor provides different output voltage with the variation of duty cycle. The output of the boost converter is coupled with a half bridge resonant converter. The resonant converter is fed from the boost converter and it produces a high frequency ac signal which is highly enviable for driving of resonant inductive link. A high frequency transformer is used to drive the resonant inductive link by properly matching the impedance. The resonant inductive link comprises of transmitter coil

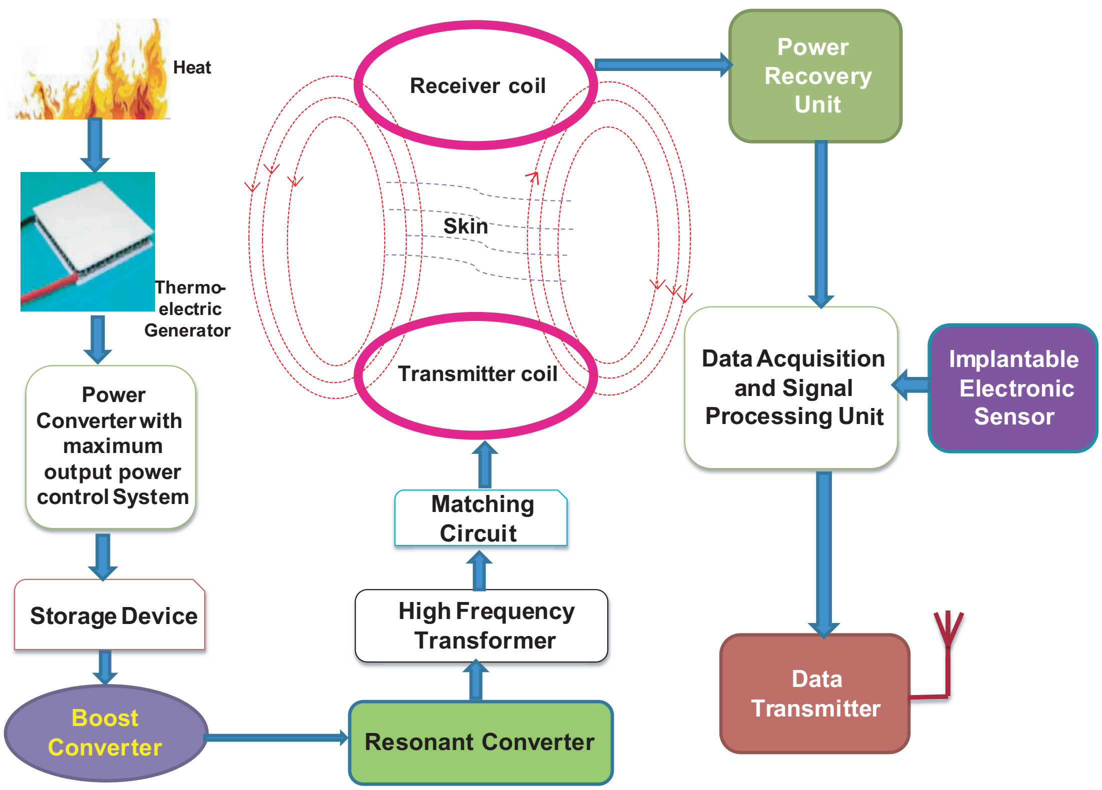

Figure 1. Schematic diagram of the process involved in the thermal energy driven resonant wireless power transfer system for implantable electronic sensor.

(combined circuit to be put outside of the animal body) with a distant receiver coil which is allied with the implantable sensor (combined circuit to be placed within the animal body). Both the transmitter coil (circular coil) and receiver coil (printed circular spiral coil to compensate the volume of implant) are magnetically coupled so as to enable wireless power transfer to the implantable temperature sensors connected across the receiver based on the magnetic resonance coupling mechanism. To provide the required power for the functioning of smart sensor entity, a power recovery unit has been placed to which the received power is delivered from the receiving coil. The body parameter of the animal will be sensed by the wirelessly powered implantable sensor, and the recorded parameter/data can be processed through the employed data gaining component along with the signal processing unit and send back through the transmitting antenna from the body to the outside data recording section, as schematically depicted in Fig. 2. For the wireless telemetry, the amplitude shift keying (ASK) digital modulation scheme is used due to its simplicity and low power consumption and the coherent detection method has been employed. This detection method uses a product detector and a phase-locked beat frequency oscillator. Also, a 2-kHz to 2-MHz bio-impedance sensor (ASIC: Application Specific Integrated Circuit) has been utilized which is designed in 180 nm CMOS technology and consumes 556 μA at 1.8 V. An experimental setup photograph is given in Fig. 3, and its equivalent circuit is depicted in Fig. 4.

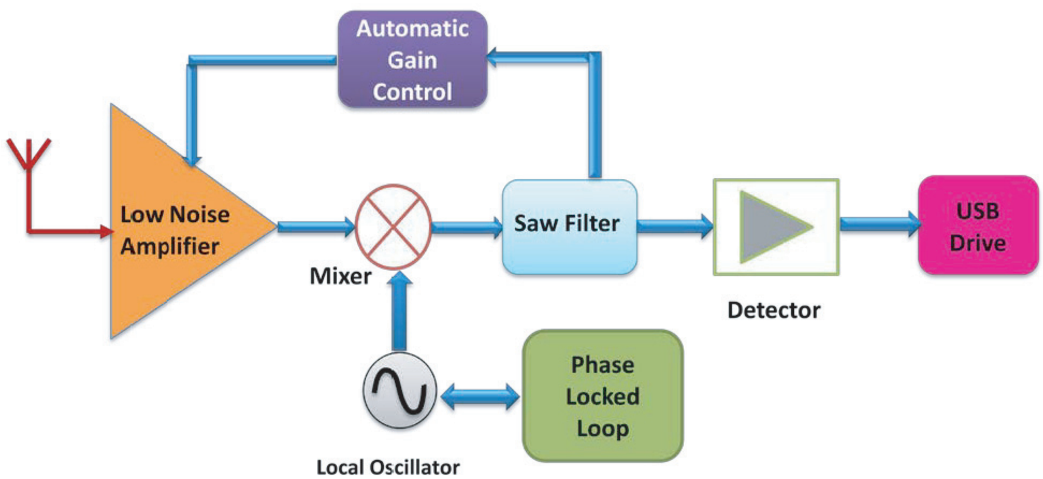

Figure 2. Health observation and outside data recording section to be kept outside the body.

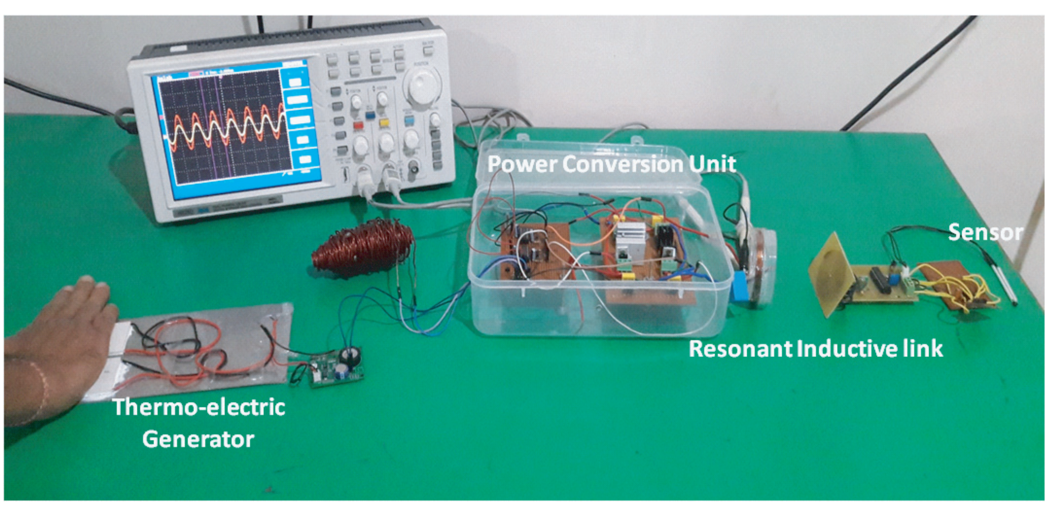

Figure 3. The experimental design photograph of thermal energy driven resonant inductively coupled wireless energization system for automated biomedical implantable temperature sensor.

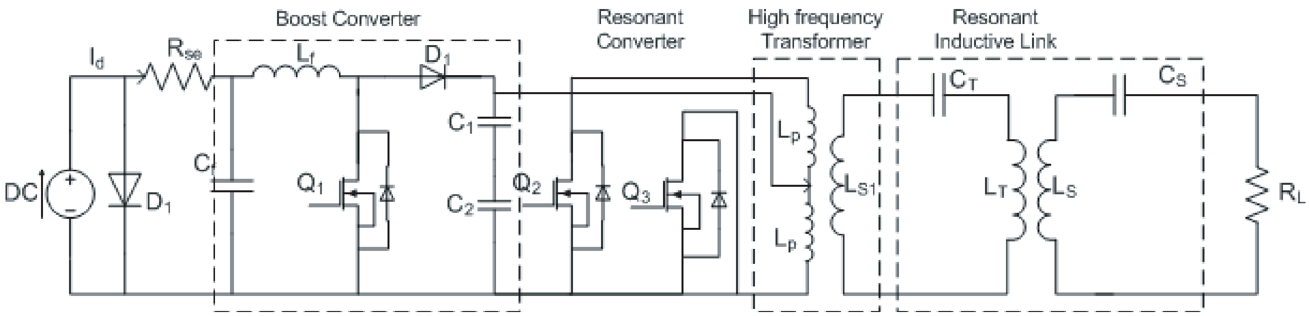

Figure 4. The equivalent circuit of the thermal energy driven resonant inductively coupled system used for wireless energization of implantable sensor.

In order to outline the relationship between the thermal difference and generated electrical power at the output of TEG module across an electric load, an equivalent mathematical model has been developed. Let us consider a thermoelectric generator consists of N pairs of p-type and n-type semiconductors, connected electrically in series and thermally in parallel, as shown in Fig. 5.

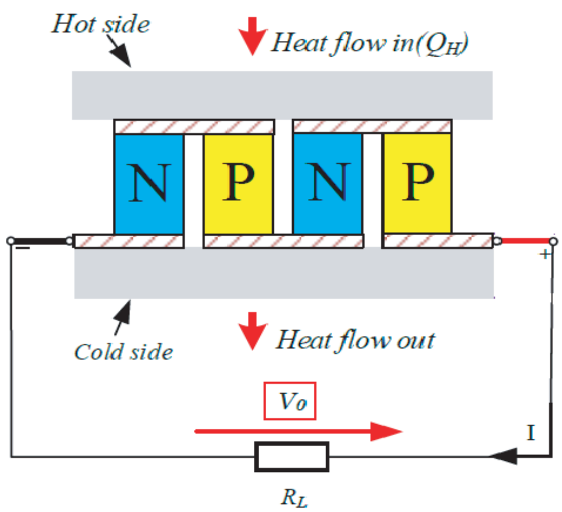

Figure 5. Equivalent model to outline the relationship between the thermal difference and generated electrical power at the output of TEG module across an electric load.

The power across the load attached with the TEG can be calculated as

$$P_{TEG} = I^2 R_L = \left(\frac{V_0}{R_L + R_{PN}} \right)^2 \cdot R_L \tag{1}$$

If N, α and ΔT represent no. of P/N legs, See-beck coefficient and the temperature difference between the two sides of the TEG module, respectively, then the voltage across the load R_L connected at the output of the TEG module is

$$V_0 = N \cdot \alpha \cdot \Delta T \tag{2}$$

So the equation can be modified as

$$P_{TEG} = \left(\frac{N \cdot \alpha \cdot \Delta T}{R_L + R_{PN}} \right)^2 \cdot R_L = \left(\frac{N \cdot \alpha \cdot \Delta T}{R_L + \frac{2N\rho L}{A}} \right)^2 \cdot R_L \tag{3}$$

where ρ is the density of materials used to manufacture P/N legs, L the length of one P/N leg, and A the cross-section area of one P/N leg, then

$$P_{TEG} = \left(\frac{N \cdot \alpha \cdot \Delta T}{R_{PN} + R_{PN}}\right)^2 \cdot R_{PN} = \frac{(N \cdot \alpha \cdot \Delta T)^2}{4 \cdot R_{PN}} \tag{4}$$

From the above relation, it has been found that the power delivered by the TEG depends on the temperature difference of the sides of TEG module. The characteristic of the power delivered by the TEG with respect to difference in temperature is illustrated in Fig. 6. It has been found that for a temperature difference of 10°C between the body temperature (38°C) and environmental temperature (28°C) on the sides of TEG module, 20 mW power is observed across the output of TEG module.

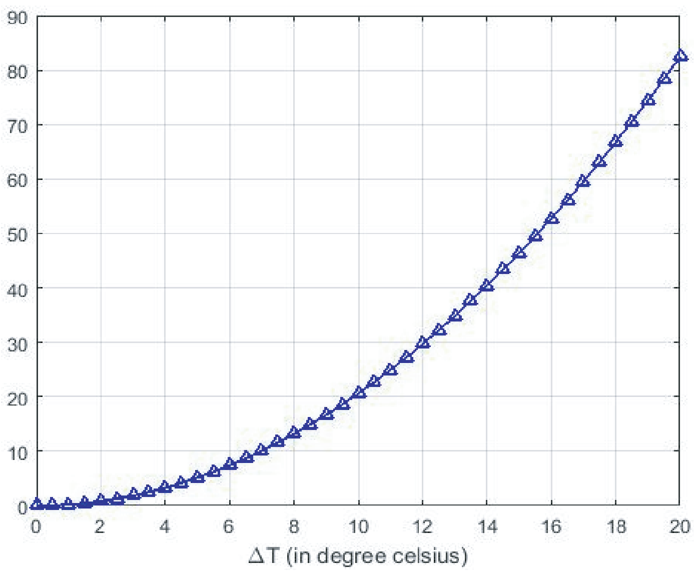

Figure 6. Characteristic of the power delivered by TEG with respect to temperature difference.

3. EXPERIMENTAL MEASUREMENTS AND DISCUSSION OF THE RESULTS

The experimental investigation has been performed to evaluate the developed method for wireless energization of implantable devices through resonant inductive link. The operating frequency (f) characteristic of the wirelessly transferred power is illustrated in Fig. 7. The received power by the receiver coil unit reaches its peak value at resonant frequency (782.2 kHz) of the inductive link with 2 cm coil separation gap. The output power drops suddenly when the system operates away from the resonance point. This is because the output of the resonant converter employed in the thermal excitation system synchronizes with the resonant frequency of the inductive link which leads to strong magnetic coupling between the coils enabling maximum power transfer.

In order to investigate the dependence of electric load on the power delivery ability of the resonant inductive link, the experiment has been carried out with respect to various loads assuming the sensor as a resistive load. The results of the receiver output power with electric load are depicted in Fig. 8. The receiver output has been found to be maximum for a particular load resistance. This is because the impedance of implantable sensor circuit unit is perfectly matched with the resonant inductive link system at this load value. The received power is observed to be 148.24 mW for the coil separation gap (d) of 2 cm and load value (R_L) of 40 Ω at the resonant frequency of 782.2 kHz.

The power transfer efficiency characteristic with respect to the coil separation gap of resonant inductive link used for wireless energization is provided in Fig. 9. The transfer efficiency is found to be decreased for the separation air gap between the coils which may be resulted from the decreased in mutual inductance and electromagnetic coupling coefficient between the coils. At 2 cm separation

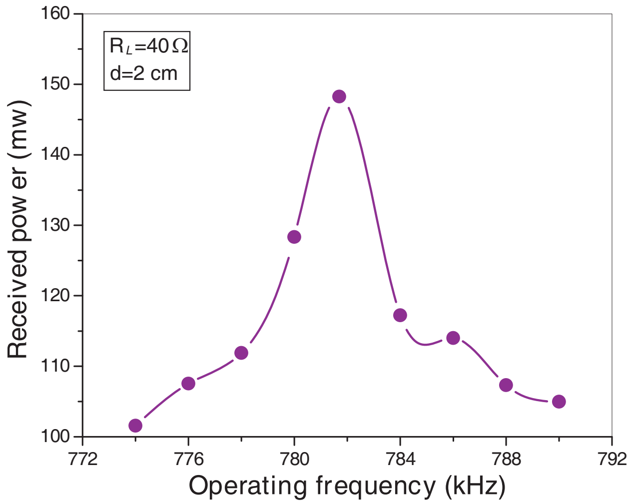

Figure 7. The frequency characteristics of the received power of the resonant inductively coupled wireless excitation system.

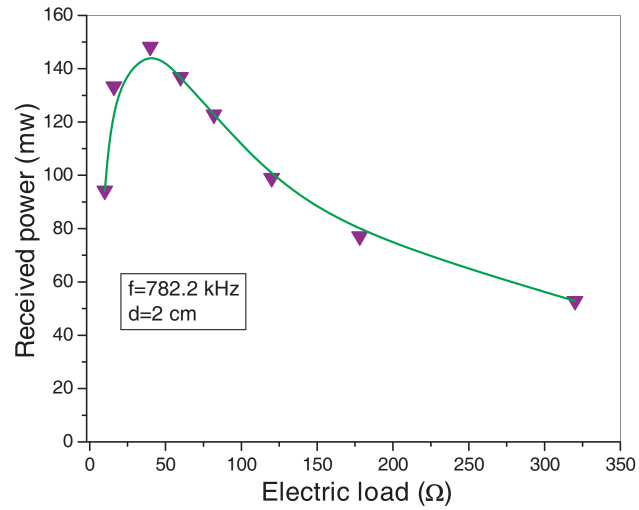

Figure 8. The dependence of wirelessly received power on the electric load resistance allied with the resonant inductive link.

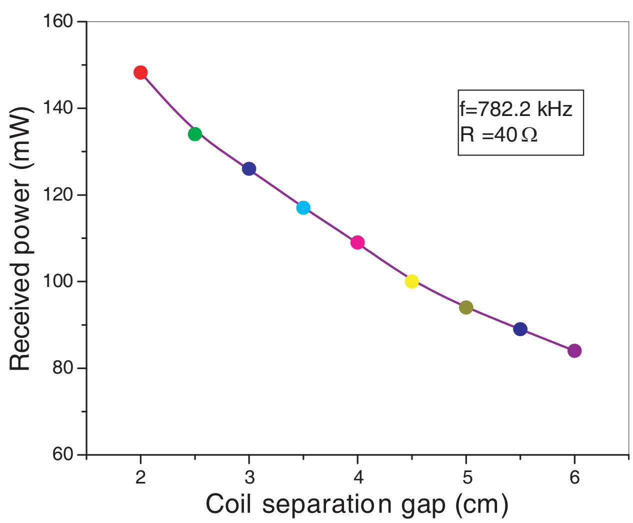

Figure 9. The experimental characteristic of received power for different separation gap of the coils of the wireless energizing system.

distance, the efficiency is observed to be about 26% at resonant frequency 782.2 kHz. The coil placement can be decided accordingly to maintain the power transfer efficiency.

The feasibility of the explored energization technique for biomedical sensing has been examined using a wirelessly energized temperature sensor to record the animal body temperature in different environmental conditions. Instead of implanting the sensor to the animal body, the experimental investigation has been carried out in the bench top set up. The temperature sensor has been kept outside of the animal body (tapped to the skin) during the course of experiments for recording the body temperature parameter to exhibit the practical demonstration The data acquisition entity collects the real-time sensed temperature data and transmits wirelessly to the data receiver unit kept apart. Utilizing the wireless technology, the automated sensing system facilitate to monitor the temperature, and put on show, store up the temperature profile on the screen of PC's using windows based GUI software. The measured temperature profile of human body in normal and fever condition, the body temperature of chicken and temperature of air in hot sunlight are displayed in Figs. 10(a)–(c). The

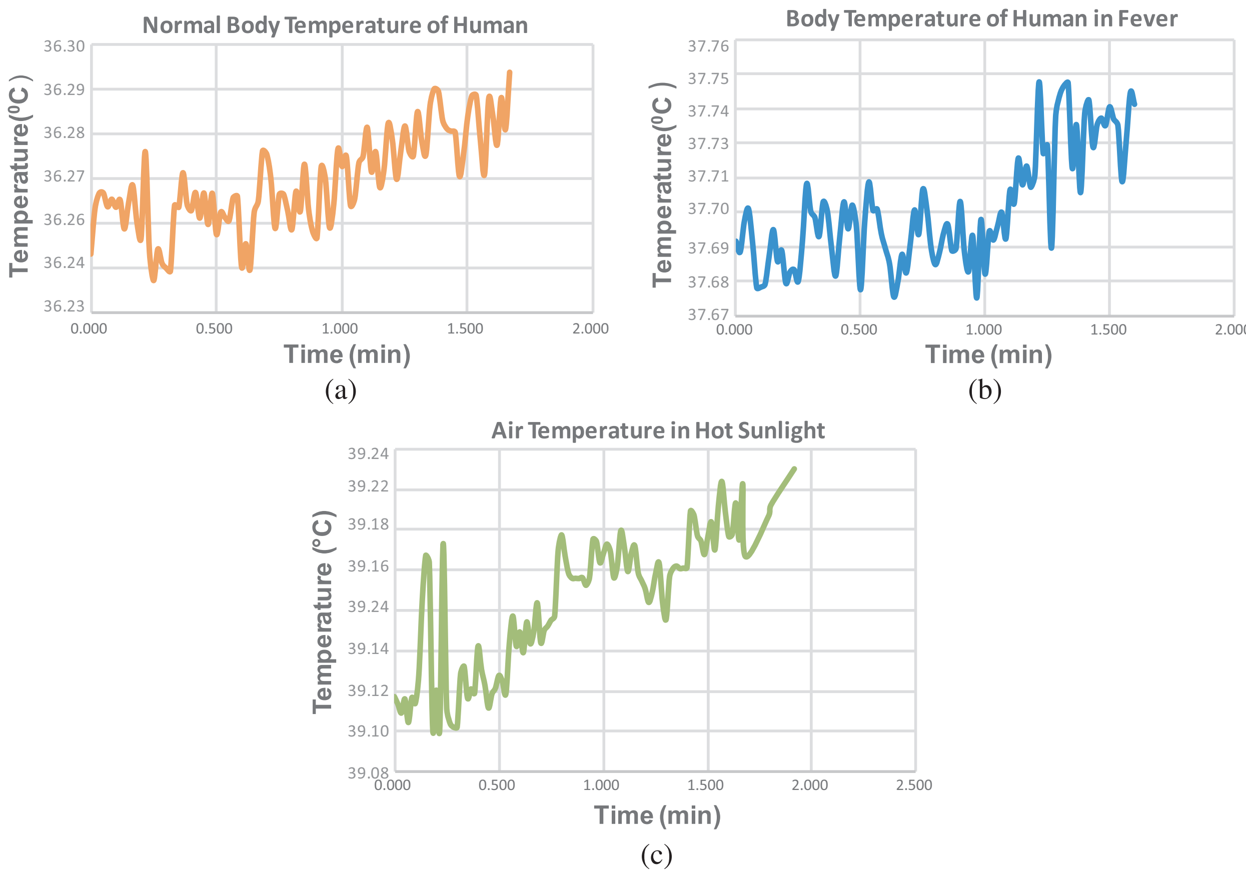

Figure 10. Measured temperature profile through the wirelessly energized sensor: (a) human body temperature in normal condition, (b) human body temperature in fever condition, (c) temperature of air.

obtained results are compared with calibrated thermometer and found in good agreement with each other. The measured results exhibit around $1\,\Omega$ resolution with an error of 2.5% and temperature sensing accuracy of 0.096°C. This experimental investigation substantiate that the proposed system has the potential to be miniaturized for real practical biomedical implant applications.

4. CONCLUSIONS

A thermal energy driven resonant inductive coupling based wireless energy transfer system has been developed for excitation of implantable smart sensor to monitor the animal body temperature parameter. In the proposed system, the harvested heat energy is converted to high frequency signal using a resonant converter and fed to the resonant inductive link to facilitate the wireless energy transfer to the attached implantable biomedical automated sensing system. The experimental investigation and the obtained results suggest that the intended technique is not only a potential solution for wireless powering of the implantable biomedical sensor but also capable to transmit externally the sensed body parameters wirelessly. The real-time body temperature of animals and room temperature have been recorded and compared with a calibrated system which ensures the accuracy of the developed prototype. To alleviate the necessities of commonly used electronic implants, the developed resonant inductive coupling system with a printed receiver coil design can be easily printed to the interior or exterior wrap of the electronic device to compensate the volume of implants inside the body. The proposed technique is highly enviable for health monitoring of patients not only in an isolated and outdoor environments but also in the areas underprivileged of grid electricity.

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