Progress In Electromagnetics Research M, Vol. 85, 175–184, 2019

Photovoltaic Driven Resonant Wireless Energy Transfer System for Implantable Electronic Sensor

Biswaranjan Swain*, Dipti Patnaik, Jayshree Halder, Praveen P. Nayak, Durga P. Kar, and Satyanarayan Bhuyan

Abstract—In order to energize the biomedical implantable electronic devices wirelessly for in vivo health monitoring of patients in an isolated, outdoor and inaccessible environment, an alternate driving energy source is highly desirable. In pertinent to this, a photovoltaic driven wireless energizing system has been explored. The system is designed to convert solar energy to a high frequency energy source so as to facilitate energy transfer through resonant inductive link to the automated bio-medical sensing system allied with the receiver unit. The received power is observed to be 286 mW for the coil separation gap of 5 cm and load value of 40 Ω at the resonant frequency of 772.3 kHz. 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 of different living beings has been experimented, and to ensure the accuracy of the developed system, the observed parameter has been matched with a calibrated system. The proposed scheme can be suitable for monitoring wirelessly other in vivo health parameters such as blood pressure, bladder pressure, and physiological signals of the patients.

1. INTRODUCTION

Biomedical electronic devices have been considered as an imperative segment to facilitate the health observation, diagnosis, and therapeutic in modern medicines for patients [1–3]. 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 either through external wired power supply to the implant internal circuits or by batteries kept inside the implantable devices [4–7]. However, the usual energizing schemes have not been preferably adopted due to the associated ubiquitous difficulties and cumbersome effect. There is a chance of snapping of wire connection, repeated replacement of low life time batteries, corrosion in the implant, and limitation in tininess due to battery size & weight [8]. This necessitates the pursuit of wireless energizing technique which is cordless, reliable, safer, smarter, and environmental friendly [9, 10]. Although the inductive coupling based wireless energization technique is acceptable for powering the sensors, but not widely adopted because of its coil configuration, large dimension and low efficiency [11], providentially, the magnetic resonant coupling based wireless technique goes to the forefront recently and also has been regarded as a viable method for powering electronic devices [12–16]. However, 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, renewable energy based energizing system can be a partial and accepted solution [17]. Thus, an alternate viable approach in the form of a photovoltaic based

Received 31 July 2019, Accepted 24 September 2019, Scheduled 2 October 2019

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

resonant wireless energizing system has been proposed for biomedical implantable electronic sensor. The proposed technique enables the transformation of solar energy to high frequency ac signal which is highly required for wireless drive of the automated biomedical sensing system allied with the resonant inductive link.

2. SYSTEM ARCHITECTURE AND OPERATING MECHANISM

The process involved in the photovoltaic driven resonant wireless power transfer system for implantable electronic sensor is schematically illustrated in Fig. 1. The health observation system consists of two sections. One is a photovoltaic driven resonance based wireless power transfer system, and the other is an implantable smart sensing section. The photovoltaic driven resonant WPT system that is placed outside of the body consists of a boost converter, a resonant converter, a high frequency transformer, and a transmitter coil. The main purposes are to convert solar energy to a high frequency ac signal of suitable level and to drive the transmitter coil at its rated value. The high frequency transformer is used to provide impedance matching between the resonant converter and transmitter coil. The implantable smart sensing section comprises a receiver coil allied temperature sensor which is to be implanted in the animal body. The circular configuration of the transmitter coil and printed circular spiral configuration of the receiver coils have been chosen in order to enhance the power transfer capability and to compensate the volume of implant. Both the transmitter coil and receiver coil are magnetically coupled so as to enable wireless power transfer to implantable temperature sensors through 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 wirelessly powered implantable sensor, and the recorded parameter/data can be processed through the employed data gaining component and 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. An experimental design photograph is shown in Fig. 3.

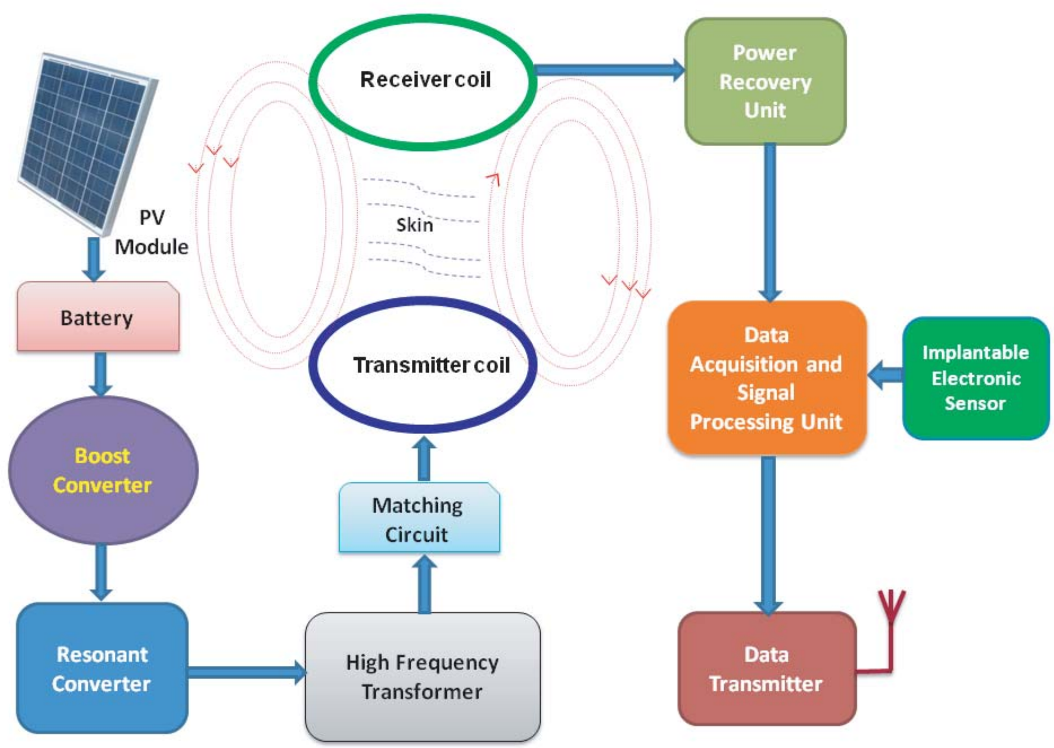

Figure 1. Schematic diagram of the process involved in the photovoltaic driven resonant wireless power transfer system for implantable electronic sensor.

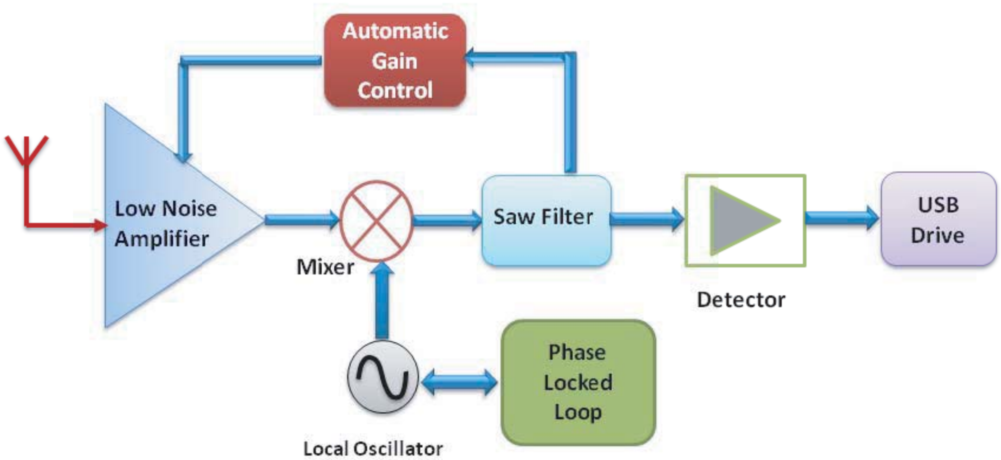

Figure 2. Health observation and outside data recording section to be kept outside the body.

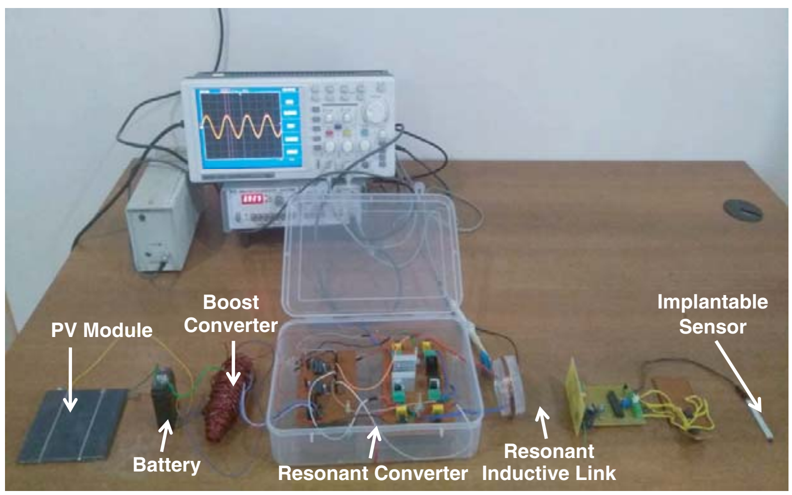

Figure 3. The experimental design photograph of solar energy driven resonant inductively coupled wireless energization system for automated biomedical implantable temperature sensor.

In the proposed method, a photovoltaic (PV) module is used to generate the voltage by harvesting the available abundant solar energy for charging the battery. To produce the power with constant amplitude (as shown in Fig. 4), a boost converter is allied with the battery as the input source. The PV 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 voltages 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 (as shown in Fig. 5) 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. A balance ratio is maintained to match the impedance of resonant circuit, and as a result, maximum power transfer occurs at resonance.

The wireless energization of implantable device through resonant photovoltaic system lies on the principle of photovoltaic energy conversion, switching mode power conversion, as well as electromagnetic resonance. When the output of the resonant converter used in the designed photovoltaic exciting system synchronizes with the resonant inductive link allied to the implantable device, the maximum power transfer occurs wirelessly.

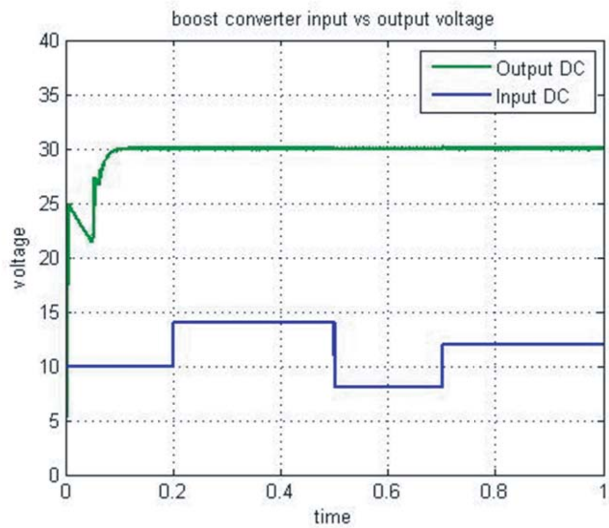

Figure 4. The boost converter input and output voltage characteristics.

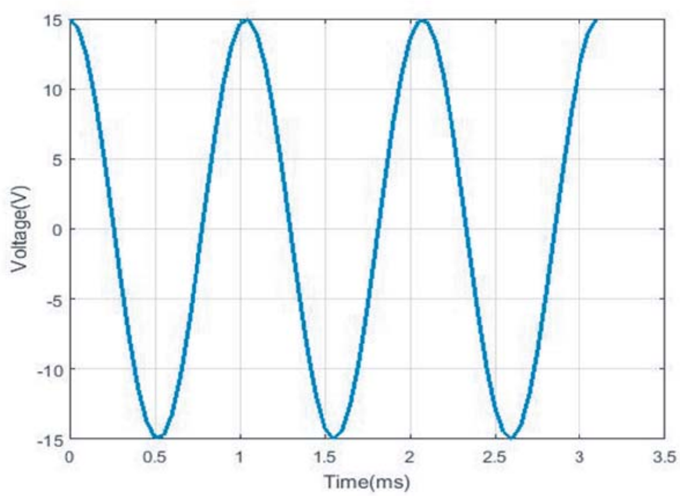

Figure 5. The resonant converter output voltage characteristics.

3. EQUIVALENT CIRCUIT MODEL

The equivalent circuit of the photovoltaic driven resonant inductively coupled system used for wireless energization of implantable sensor is depicted in Fig. 6. The PV generated voltage (V_{pv}) is stepped up by the boost converter with suitable switching frequency. The regulation of PV generated voltage by a boost converter can be explained through the voltage-sec balance equation [18]

$$V_{pv} \cdot DT_s + V_{res}(1 - D)T_s = 0 \tag{1}$$

where V_{pv} is the PV generated voltage, V_{res} the output regulated dc voltage, T_s the switching time, and D the duty ratio ($0 < D < 1$).

In order to achieve a constant regulated output voltage which may vary with the variation of duty cycle, it is necessary to minimize the ripple content with properly chosen filter inductor (L_f) and capacitor (C_f). The voltage ripple (Δv) and current ripple (Δi) are given by

$$\Delta v = \frac{V_{res}}{RC_f} DT_s \tag{2}$$

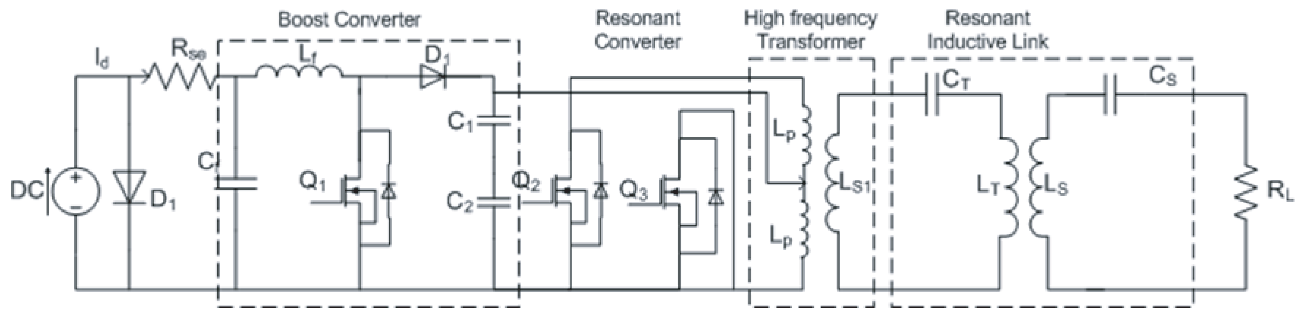

Figure 6. The equivalent circuit of the photovoltaic driven resonant inductively coupled system used for wireless energization of implantable sensor.

$$\Delta i = \frac{V_{pv}}{L_f} DT_s \tag{3}$$

The output of the boost converter is coupled with a half bridge resonant converter in which the switching elements are connected with an anti-parallel diode. The voltage at the output of resonant converter is [19]

$$v_0 = \sum_{n=1,3\ldots}^{\infty} \frac{2V_{res}}{n\pi} \sin(n\omega t). \tag{4}$$

The fundamental output voltage of the resonant inverter

$$V_P = \frac{\sqrt{2}V_{res}}{\pi} \tag{5}$$

The output ac voltage of the resonant inverter (v_0) is fed to the transmitter coil of resonant inductive link. By considering the implantable device as a resistive load (R_L), the received output power can be calculated as follows:

$$P_L = \frac{V_P^2 \omega_0^2 M^2 R_L}{R_P^2 (R_S + R_L)^2 + \omega_0^4 M^4 + 2\omega_0^2 M^2 R_P (R_S + R_L)} \tag{6}$$

where R_P & R_S are the effective series resistances of the transmitting and receiver coil windings of the resonant inductive link; M is the mutual inductance between the coils; ω_0 is the operating resonant frequency of the resonant inductive link.

The power transfer efficiency (PTE) of the wireless system is given by

$$\eta(\%) = \frac{P_L}{P_{in}} \times 100 \tag{7}$$

It is observed from the equation that the power delivered to the implantable device depends on the fundamental component of the output voltage of resonant converter associated with the photovoltaic system coil properties, operating frequency, mutual coupling, and separation gap between the coils.

4. RESULTS AND DISCUSSION

In order to realize the effect of operating frequency on the power level at the input and output of resonant inductive link, the experimental measurement has been performed, and their characteristics are illustrated in Fig. 7. The output received power reaches its peak value at the resonant frequency of 772.3 kHz for vertical spacing of 5 cm between the coils. Also, the frequency dependency of the power transfer efficiency has been examined and is depicted in Fig. 8. Both the output power and power transfer efficiency drop suddenly when the system operates away from the resonance point. This is because the output of the resonant converter employed in the photovoltaic exciting system synchronizes

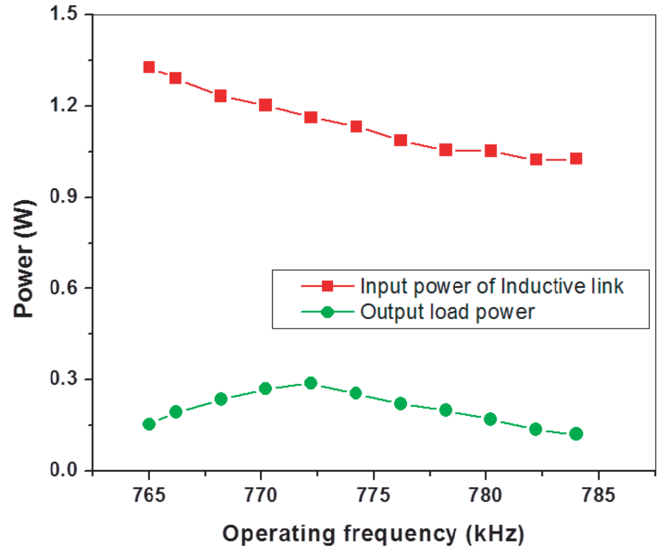

Figure 7. The effect of operating frequency on the power level at the input and output of resonant inductive link.

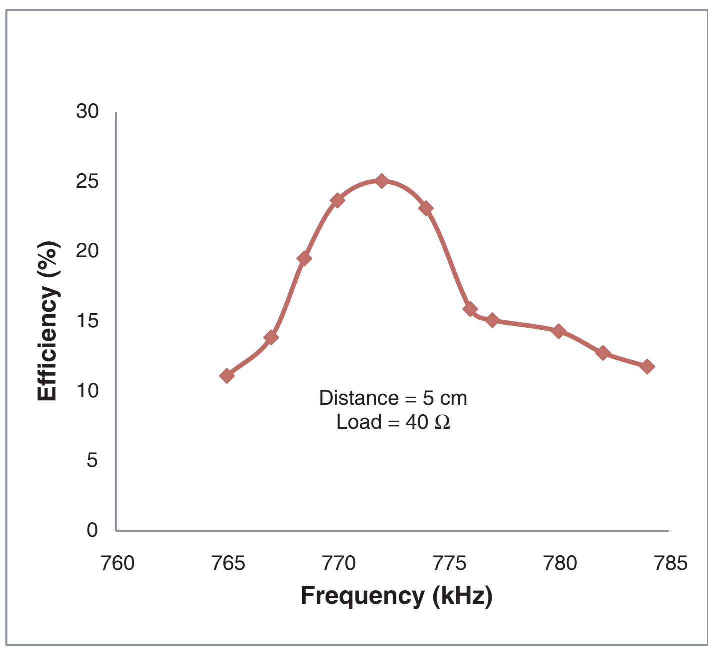

Figure 8. The experimental frequency characteristic of power transfer efficiency.

with the resonant frequency of the inductive link. The strong magnetic coupling leads to maximum power transfer between the coils.

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. 9. 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 286 mW for the coil separation gap of 5 cm and load value of 40 Ω at the resonant frequency of 772.3 kHz.

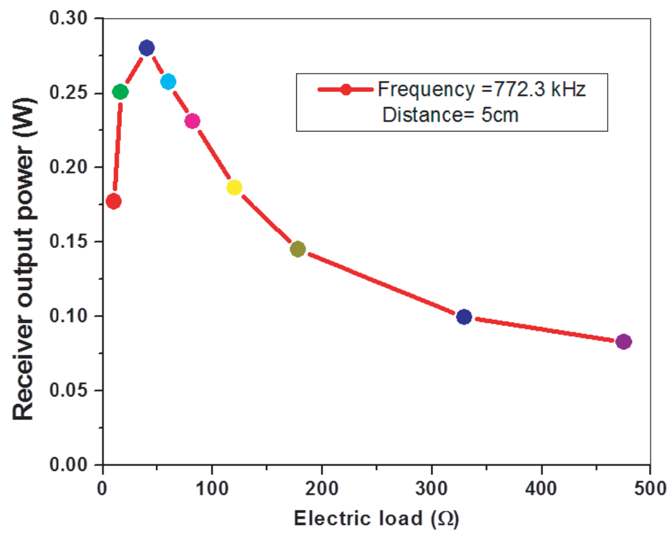

Figure 9. The dependence of wirelessly received power on the electric load resistance allied with the resonant inductive link.

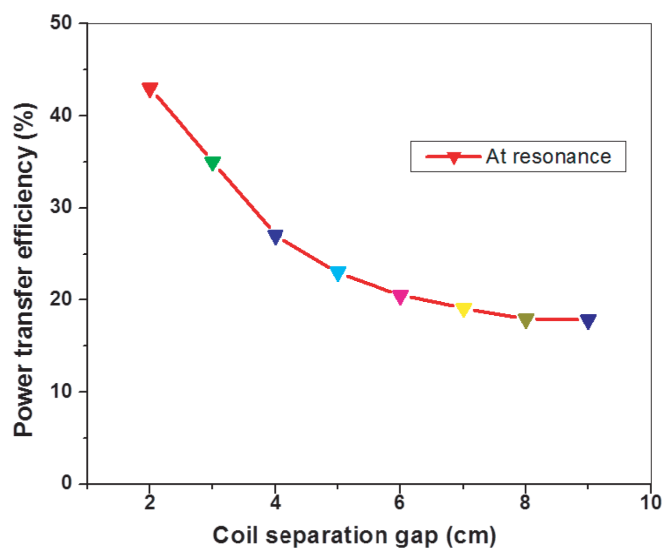

Figure 10. The experimental frequency characteristic of power transfer efficiency for different separation gap of the coils of wireless energizing system.

The PTE characteristic with respect to the coil separation gap of resonant inductive link used for wireless energization is given in Fig. 10. It is seen that the efficiency declines with increase in separation gap of the coils. Hence it can be affirmed that the depreciation in mutual coupling leads to the deterioration in PTE.

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 setup. 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 proposed system has the potential to be miniaturized for real practical biomedical implant applications. The data acquisition entity collects the real-time sensed temperature data and transmits wirelessly to the data receiver unit

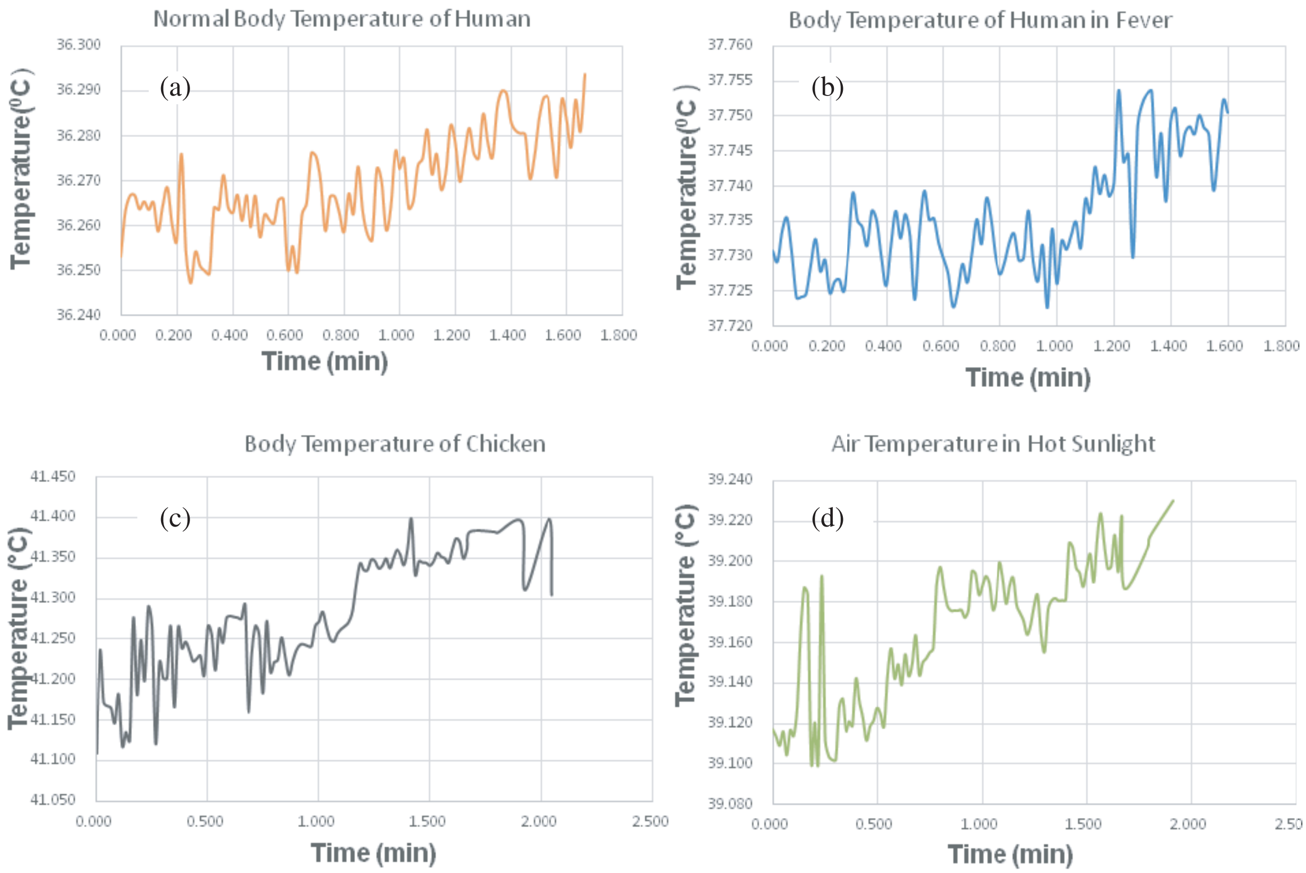

Figure 11. Measured temperature profile through the wirelessly energized sensor: (a) human body temperature in normal condition, (b) human body temperature in fever condition, (c) the body temperature of chicken, (d) temperature of air in hot sunlight.

kept apart. Utilizing the wireless technology, the automated sensing system facilitates monitoring of the temperature, puts on show, and stores 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 conditions, the body temperature of chicken, and temperature of air in hot sunlight are displayed in Figs. 11(a)–(d). The obtained results are compared with calibrated thermometer and found to be in good agreement with each other.

5. CONCLUSIONS

A photovoltaic driven resonant inductive coupling based wireless energy transfer system has been developed for excitation of an implantable smart sensor to monitor the animal body temperature parameter. In the proposed system, the harvested solar 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. In order to realize the effect of operating parameters on the performance of photovoltaic driven wireless power transfer system, both the theoretical analysis and experimental investigation have been carried out. It is found that the power delivered to the implantable device depends on the fundamental component of the output voltage of resonant converter associated with the photovoltaic system, transmitting and receiving coil properties, operating frequency, mutual coupling, and separation gap between the coils. The received power is observed to be 286 mW for the coil separation gap of 5 cm and load value of 40 Ω at the resonant frequency of 772.3 kHz. In order to validate the obtained experimental and calculated theoretical results, circuit simulation of the resonant photovoltaic system for wireless excitation has been carried out. It is found that interestingly all the results agree well with each other. Utilizing the proposed photovoltaic energy driven wireless technology, the automated sensing system facilitates the monitoring of the temperature of human body in normal and fever conditions, the body temperature of chicken, and temperature of air in hot sunlight. The experimental investigation and obtained results suggest that the intended method is not only a potential solution for wireless powering of an implantable biomedical sensor but also capable to transmit 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 system. The proposed technique is highly enviable for in vivo health monitoring of patients not only in an isolated and outdoor environments but also in the areas underprivileged of grid electricity.

REFERENCES

1. Rasouli, M. and S. Jay, "Energy sources and their developments for application in medical devices," *Expert Review of Medical Devices*, Vol. 7, 693–709, 2010.
2. Puers, R. and G. Vandevoorde, "Recent progress on transcutaneous energy transfer for total artificial heart system," *Artificial Organs*, Vol. 25, 400–405, 2001.
3. Kiourti, A., K. A. Psathas, J. R. Costa, C. A. Fernandes, and K. S. Nikita, "Dual-band implantable antennas for medical telemetry: A fast design methodology and validation for intra-cranial pressure monitoring," *Progress In Electromagnetics Research*, Vol. 141, 161–183, 2013.
4. Wang, G., W. Liu, M. Sivaprakasam, and G. A. Kendir, "Design and analysis of adaptive transcutaneous power telemetry for biomedical implant," *IEEE Trans. Circuits and System*, Vol. 52, 2109–2117, 2005.
5. Vidal, N., S. Curto, J. M. Lopez-Villegas, J. Sieiro, and F. M. Ramos, "Detuning study of implantable antennas inside the human body," *Progress In Electromagnetics Research*, Vol. 124, 265–283, 2012.
6. Shin, S. Y., B. Saravanakumar, A. Ramadoss, and S. J. Kim, "Fabrication of PDMS based triboelectric nanogenerator for self sustained power source application," *Int. J. Energy Research*, Vol. 40, 288–297, 2015.
7. Ozeri, S. and Shmilovit, "Ultrasonic transcutaneous energy transfer for powering implanted devices," *Ultrasonics*, Vol. 50, 556–559, 2010.
8. Swain, B., P. P. Nayak, D. P. Kar, S. Bhuyan, and L. P. Mishra, "Wireless energizing system for an automated implantable sensor," *Review of Scientific Instruments*, Vol. 87, 074708, 2016.
9. Smith, S., T. Tang, and J. Terry, "Development of a miniaturised drug delivery system with wireless power transfer and communication," *Inst. Eng. Technol. Nanobiotechnol.*, Vol. 1, 80–86, 2007.
10. Ghovanloo, M. and K. Najafi, "A wireless implantable multichannel microstimulating system-on-a-chip with modular architecture," *IEEE Trans. Neural Syst. Rehab. Eng.*, Vol. 15, 449–457, 2007.
11. Riistama, J., J. Vaisanen, S. Heinisuo, H. Harjunpa, S. Arra, K. Kokko, M. Antyla, J. Kaihilahti, P. Heino, M. Kellomaki, O. Vainio, J. Vanhala, J. Lekkala, and J. Hyttinen, "Wireless and inductively powered implant for measuring electrocardiogram," *Med. Bio. Eng. Comput.*, Vol. 45, 1163–1174, 2007.
12. Ram Rakhyani, A., S. Mirabbasi, and M. Chiao, "Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 5, 48–63, 2011.
13. Swain, B., P. P. Nayak, D. P. Kar, and S. Bhuyan,, "Thermal energy based Resonant inductively coupled wireless energization method for implantable biomedical sensor," *Progress In Electromagnetics Research M*, Vol. 67, 129–136, 2018.
14. Bhuyan, S., S. K. Panda, K. Sivananda, and R. Kumar, "A compact resonace-based wireless energy transfer system for implanted electronic devices," *International Conference on Energy, Automation and Signal*, 1–3, 2011.

15. Ghanad, M. A., M. Green, and C. Dehollain, "A 30 μW remotely powered local temperature monitoring implantable system," *IEEE Transcations on Biomedical Circuits and Systems*, Vol. 11, 54–63, 2017.
16. Kar, D. P., S. S. Biswal, P. K. Sahoo, P. P. Nayak, and S. Bhuyan, "Selection of maximum power transfer region for resonant inductively coupled wireless charging system," *AEU — International Journal of Electronics and Communications*, Vol. 84, 84–92, 2018.
17. Ayazian, A., V. A. Akhavan, E. Soenen, and A. Hassibi, "A photovoltaic-driven and energy autonomous CMOS implantable sensor," *IEEE Transactions on Biomedical Circuits and Systems*, Vol. 6, 336–343, 2012.
18. Rashid, M. H., *Power Electronic Circuits Devices and Application*, Pearson, New Jersey, 2010.
19. Hart, D. W., *Power Electronics*, McGraw-Hill, New York, 2011.