

## RESEARCH ARTICLE

# Design of a wireless power transfer system for assisted living applications

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*Advances in material science and semiconductor technology have enabled a variety of inventions to be implemented in electronic systems and devices used in the medical, telecommunications, and consumer electronics sectors. In this paper, a wireless charging system is described as a wearable body heater that uses a chair as a transmitter (Tx). This system incorporates the widely accepted Qi wireless charging standard. Alignment conditions of a linear three-element coil arrangement and a  $3 \times 3$  coil matrix array are investigated using voltage induced in a coil as a performance indicator. The efficiency obtained is demonstrated to be up to 80% for a voltage of over 6.5 Volts and a power transfer of over 5 Watts. Our results and proposed approach can be useful for many applications. This is because the wireless charging system described herein can help design seating areas for the elderly and disabled, commercial systems, consumer electronics, medical devices, electronic textiles (e-textiles), and other electronic systems and devices.*

**Keywords:** Coil, Near field, Array, Wireless power transfer, Assisted living applications

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## 1. INTRODUCTION

Smart clothing is a new trend in wearable technology aimed at improving human life and satisfaction. Such clothing is made using combinations of micro-electronics embedded in fabrics to create functional and fashionable solutions that meet people's everyday needs. An area of interest is assisted living (AL), which takes into consideration the delicate needs of elderly individuals. In many countries, such as the USA and European Union (EU) countries, modern medicine has increased the longevity of people's lives. However, such countries are also experiencing a decreasing birth-rate that is leading to a disproportionate amount of people aged 65 and above when compared to the younger working population [1]. With current trends, it is estimated that, in the next 30 years, the elderly (i.e. individuals aged 65 or older) will outnumber their younger counterparts in the EU, for example, two to one [2]. This phenomenon will create a higher demand for AL solutions that can be used to provide long-term care to the aging population [3].

The primary objective of AL technologies is to improve lives by providing security, comfort, and independence [4]. These technologies can be applied to different environments,

from homes and offices to outdoor public facilities [5–16]. However, devices used in an AL system requires a continuous source of power which can be provided by supportive batteries (e.g. lithium-ion batteries) [17]. However, currently available batteries cannot always meet the demands of the devices that make up an AL system [18]. That is, prolonged use of an AL system's devices eventually requires battery recharging and replacement, which can be a tedious, expensive, and complicated task for the elderly and other individuals [15]. For example, replacing batteries in biomedical implants is expensive and a complex procedure. Research into energy harvesting [19–21], wireless charging [22–26], battery and power management [27–29] has been conducted for AL systems to improve the functionality and efficiency of device batteries.

Wireless charging offers a great solution to the problems with batteries as described above. For example, this way of charging batteries can be more convenient to a user of an AL system than wired charging and some early examples have been demonstrated [18], [30], and [31]. To address safety concerns of the technology, regulations and standards of implementing wireless power transfer (WPT) for charging should also be considered [32–38]. Currently, two main commercial WPT standards exist: (i) the Qi standard created by the wireless power consortium (WPC) and (ii) the A4WP standard the air fuel alliance (AFA). Both standards enable wireless charging techniques that use magnetic induction to transfer power from a transmitter (Tx) to a corresponding receiver (Rx) within a target device. WPC's Qi and AFA's A4WP standards are discussed extensively in [39–41]. The two standards meet the international and regional regulations on safety and electromagnetic interference set up by government and health agencies [32]. Safety

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considerations are made by selecting a non-radiative WPT system design described in [42–50]. More specifically, the research presented in this paper is directed to exploring the design of a WPT system for wirelessly charging a wearable heating belt.

The challenges faced by these wirelessly charged devices include: (i) electromagnetic safety levels that lead to regulatory restrictions, which require a low power source with higher transmission efficiency [47]; (ii) limited range of operation, which leads to positioning issues of the transmitter and receiver [48]; and (iii) problems with integrating the transmitter and receiver in a seamless way to the user's everyday environment [49, 50].

Works in [18], [30], [51–54] have also demonstrated high power transmission efficiency (PTE) using different approaches. For example, using small biomedical implant coils a PTE of 58% was achieved in [18]. Metamaterials have also been used to increase PTE in medium power applications [30]. In [52] and [53], a transmitter coil array was used to improve PTE to up to 85 and 50%, respectively.

Positioning issues have also been researched and overcome using different techniques in some works in [52], [55], [56], and [57]. In [52], primary coils were embedded into a desk surface which significantly improved the charging area. Further, [55] used a sequence of switchable couples of coils to adopt a transmitting link side that retains its coupling coefficient for a continuously moving receiver. In [56], a similar concept to [52] was adopted using magnetically coupled resonant wireless power, while [57] used a bowl-shaped transmitter coil for free positioning.

In our proposed design as reported in this paper, which is based on the widely accepted  $Q_i$  wireless charging standard, the transmitter of the WPT system is integrated within a backrest of a chair, while the WPT system's receiver is integrated in the user's belt together with a novel far-infrared heating element (see Figs 1(a) and 1(b)). The belt can be charged

while its user is seated in the chair. This paper also investigates and examines alignment and power transfer conditions of the charging area on a chair's backrest, considering different coil arrangements and arrays. The WPT system proposed can also be used in multiple charging scenarios, including AL environments. In this way, the proposed WPT charging and heating system can be seamlessly integrated into the user's life with ease and comfort.

## II. WIRELESS SYSTEM DESIGN

The major factors that affect the performance of the WPT system described herein are: (i) distance and misalignment between the transmitter and receiver; and (ii) power transfer between the transmitter and receiver. Both are attributable to inductive power transfer, which is specified by the  $Q_i$  standard [39]. Table 1 shows the initial design constraints of the system.

When the separation distance of the coils for the system is smaller than  $1/10^{\text{th}}$  of the wavelength of magnetic field, an Equivalent Lumped Parameter Circuit Model of the system can be made as further described in [58].

The first constraint requires that the receiver to be near the transmitter of the WPT system. More specifically, and as shown in Fig. 1(b), the belt to be charged (which includes

Table 1. System specifications.

| Parameters        | Value  |
|-------------------|--------|
| $P_{out}$ (W)     | 5      |
| $V_{out}$ (V)     | 5–7    |
| $V_{in}$ (V)      | 12     |
| Transfer distance | < 3 cm |
| Efficiency        | 70–80% |

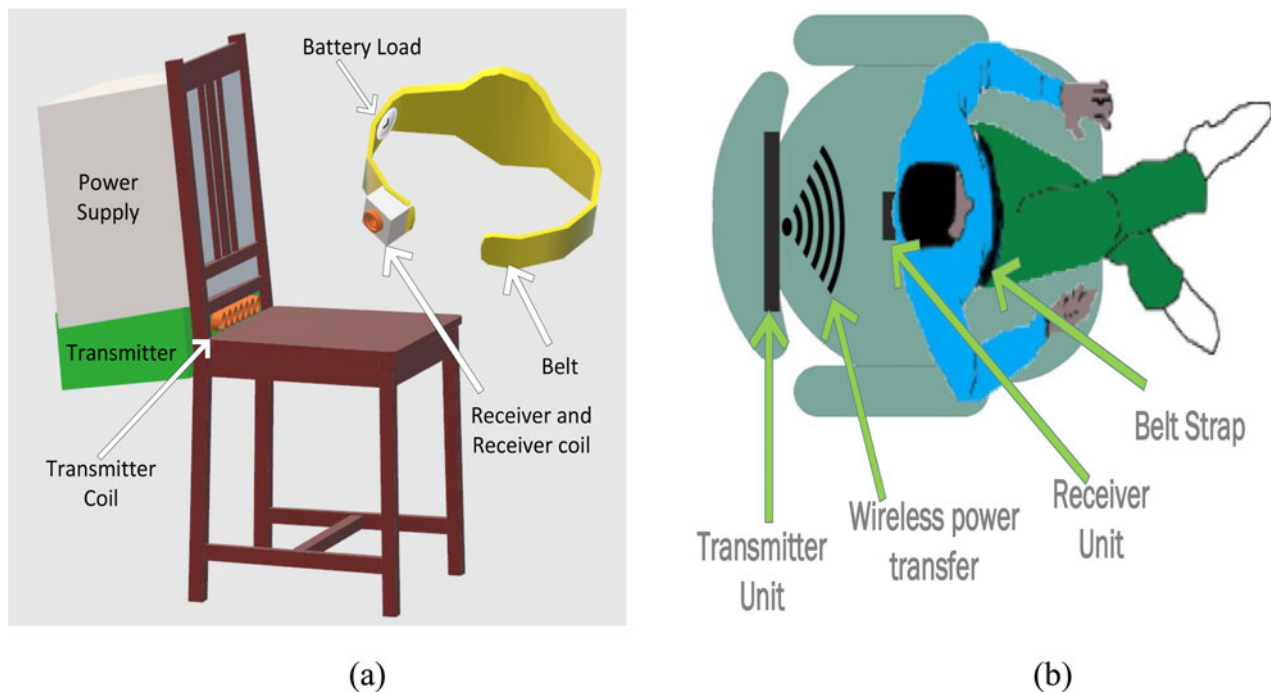


Fig. 1. (a) Illustration of the wireless power system to power a belt and integration into a chair. (b) Setup showing the working concept of the WPT system when the user is sitting on the chair. The actual wearable belt can be seen in Fig. 2.

the receiver) must be close to the chair's backrest (which includes the transmitter). Furthermore, the second constraint requires power transfer in our WPT system to occur at any sitting position. The proposed WPT system overcomes the constraints described above by using an array of coils to be embedded in the backrest of the chair (previously shown in Fig. 1) and as similarly used in [52] and [56]. Thus our proposed design as described in Fig. 2 can increase the coverage area for WPT.

The main design constraints of the coil size of the system include the physical dimensions of the belt (for the receiver) and load (li-ion battery pack). The battery has a nominal input voltage of 7 V and an input power of 5 W as specified in [59].

Our design process is shown in Fig. 3 and physical dimensions of the coils were used as initial input parameters to calculate the required self-inductance of the coils and mutual inductance by the theory reported [60], which was then optimized based on the power transfer efficiency (PTE). The receiver coil had restrictions due to the belt size while there were no size constraints for the transmitter, other than it needed to fit within a chair.

$$\eta = \frac{1}{1 + \left[ A \frac{R_1}{R_L} \right] + \left[ R_2 \frac{R_L}{(wL_2)^2} \right]} \quad (1)$$

The circuit was then tuned to obtain the resonant capacitors for the primary and secondary coils by following [61]. These parameters were then used in the simulation environment for further optimization and where the Keysight software Advanced Design System (ADS) was employed.

### A) Transmitter parameters

The transmitting unit is based on the WPC1.1 Qi specification with a 5W power level [62]. A WPC A29-type coil was used and characterized with parameters as in [63]. The transmitter coil is fabricated from litz wire with nylon spinning having

180 strands of no. 40 AWG (0.08 mm diameter). The measured inductance and quality factor of the transmitter coil were 10  $\mu$ H and 90, respectively. A ferrite sheet was placed underneath the coil to shield the electronics in the base of the charger [64].

### B) Receiver parameters

The design constraints for the individual receiving coil ( $32 \times 48 \text{ mm}^2$ ) was more due to the limited dimensions of the textile belt. During the initial design phase, efforts were made to ensure that the employed receiver coil was able to provide a suitable mutual inductance [65] and thus provide sufficient coupling; i.e. the coil had an inductance of 15  $\mu$ H and a quality factor of 60 (Fig. 4 illustrates the design process in terms of size, load resistance and coupling distance). Table 2 shows the performance data of the transmitter and receiver modules.

## III. WIRELESS POWER DESIGN

The wireless system transmits power from a transmitter embedded in a chair then a belt containing the receiver unit receives and harvests the power. The harvested power is used to provide a regulated supply voltage suitable for charging the lithium-ion battery. The connection between the battery and the receiver has been implemented on a breadboard. Voltmeters and ammeters were connected to allow power consumption to be measured, as shown in Fig. 4.

## IV. SYSTEM MODELING AND SIMULATION

Modeling the wireless power system (transmitter and receiver modules) through a simulation tool is an important part of the design before implementing the physical system. This kind of simulation-based approach can help to estimate and quantify expected outcomes of the real time experimentation. The

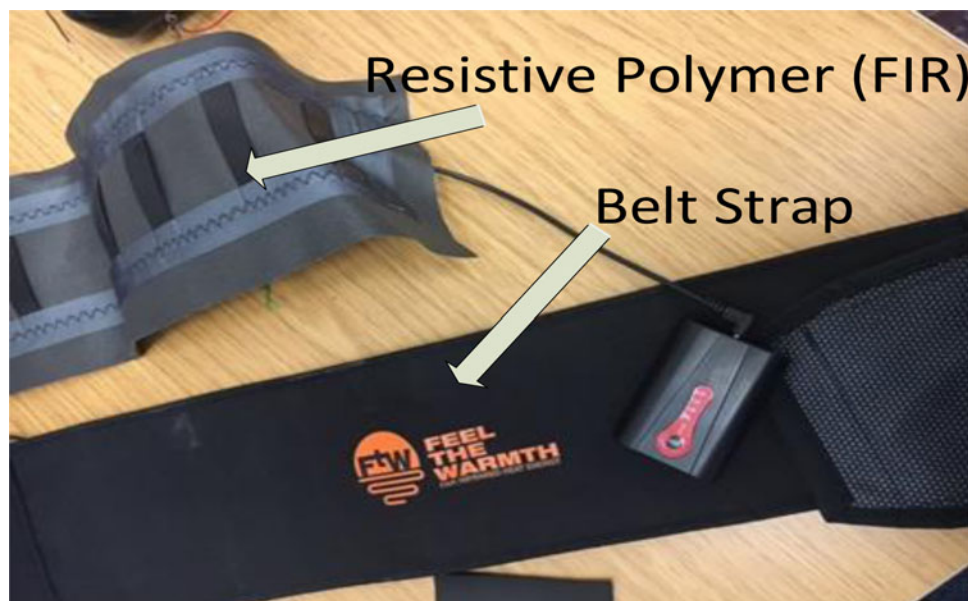


Fig. 2. Wearable belt with the charging element.

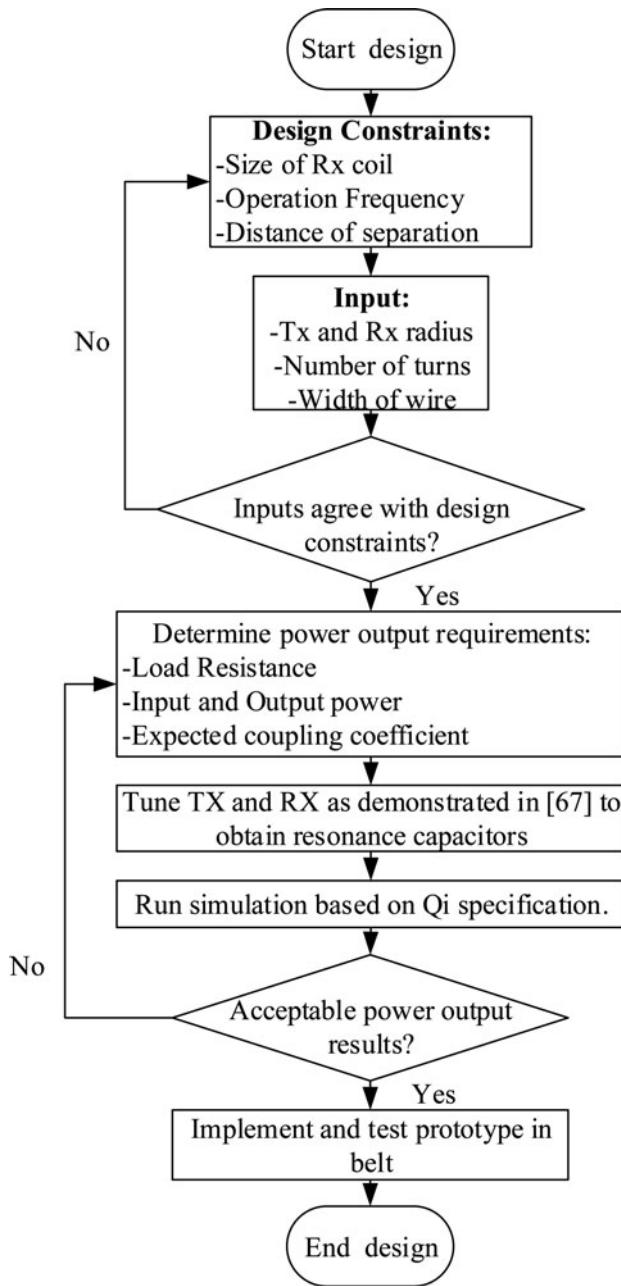


Fig. 3. Flowchart of the design methodology for the proposed WPT system.

simulation software Keysight ADS was used to obtain the power output at the receiver for any coupling condition using coil types of the chosen transmitter and receiver modules.

The transmitter and receiver modules operated using inductive coupling regulated by the  $Qi$  standard which operates at frequencies between 100 and 200 kHz. The transmitter module is made up of an oscillator capable of producing the required resonant frequency. An amplifier then drives alternating current into the primary coil. The receiver converts the signal to DC through rectifying circuits [39].

The combination of the BQ500215EVM-648 wireless power transmitter and the BQ51025EVM-649 receiver shown in Fig. 8 are expected to give an output of 7 V at a maximum current of 1 A.

### A) Coupling factor and coil modeling

Coupling factor quantifies the strength of magnetic field generated by the transmitter coil and it varies between 0 and 1. It must be noted that, when  $k = 1$  this represents perfect coupling. Coupling is also highly dependent on the distance between the coils as will be shown in the paper.

From [66] and [67] the inductance of the transmitter and receiver modules were obtained respectively to calculate the coupling coefficient,  $k$ , before calculating the mutual inductance between the coils,  $M$ . Also, the coupling factor can be measured from an existing system as a relative open loop voltage,  $u$ , it can be given as follows from (5a) in [61]:

$$u = \frac{U_2}{U_1} = k\sqrt{\frac{L_{22}}{L_{11}}}, \tag{2}$$

where  $U_1$  and  $U_2$  are the voltages applied to coil,  $L_{11}$  is the self-inductance of the transmitter coil, and  $L_{22}$  is the self-inductance of the receiver coil. These parameters are also related to the general set of equations for coupled inductors as seen in [68]:

$$\frac{U_1}{j\omega} = L_{11}I_1 + MI_2 = L_{11}I_1 + \Phi_{12}, \tag{3}$$

$$\frac{U_2}{j\omega} = MI_1 + L_{22}I_2 = \Phi_{21} + L_{22}I_2. \tag{4}$$

Inserting equation (2) into equations (3) and (4) we get the following:

$$\frac{U_1}{j\omega} = L_{11}I_1 + \Phi_{12}, \tag{5}$$

$$\frac{U_2}{j\omega} = \Phi_{21} + L_{22}I_2. \tag{6}$$

These equations show that the voltage can be expressed in the form of flux density. This condition is possible when the transmitting and receiving coils are coupled strongly with each other, in other words, a very small distance is separating them [69]. The overall measured inductance is given by  $L_S$  in [61], which is:

$$L_S = L_{11} + L_{22} + (2M). \tag{7}$$

### B) Resonant capacitors

The receiver circuit has two resonant capacitors  $C_s$ , and a series resonant capacitor and  $C_{sp}$ . These capacitors along with the receiver coil make up a dual resonant circuit. The two capacitors are used to tune the receiver coil and by the  $Qi$  standard, should be sized correctly based on the WPC specification [62], and where the receiver coil is then placed on the spacer, and  $L_{rx}$  is measured with a stimulus of 1-V RMS and 100 kHz. These capacitors can be further calculated using the 100 kHz resonant frequency:

$$C_p = \frac{1}{[100kHz \ 2\pi]^2 L_p}, C_s = \frac{1}{[100kHz \ 2\pi]^2 L_S}, \tag{8}$$

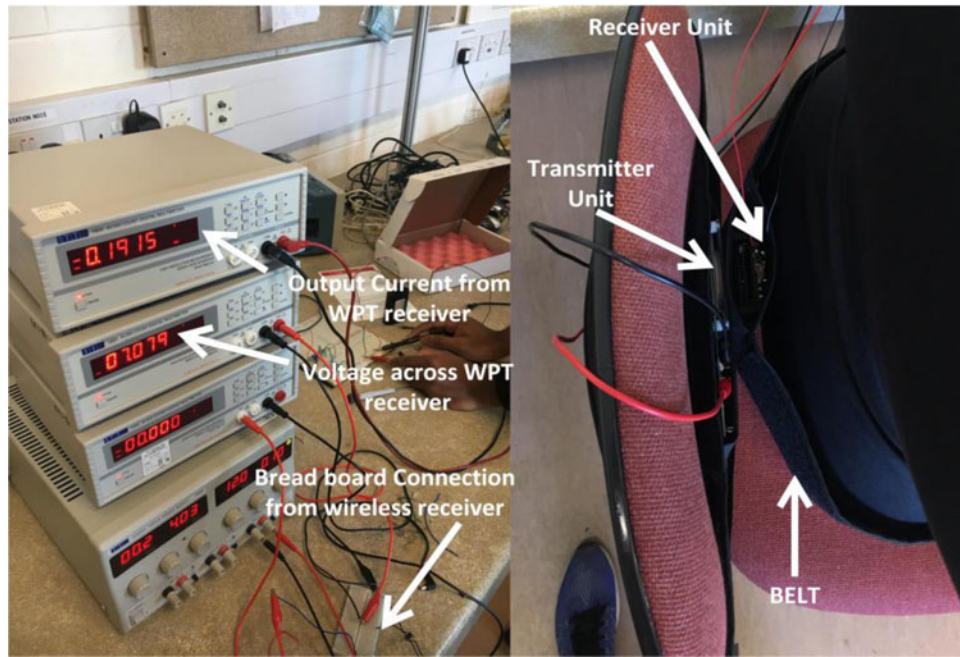


Fig. 4. Left side shows measurement equipment and setup. Right side shows the wireless power system operating in the belt and a chair.

and  $C_{sp}$  is the secondary resonance considering 1 MHz:

$$C_{sp} = \frac{1}{[1\text{MHz } 2\pi]^2 \left[ L_s - \frac{1}{C_s} \right]} \tag{9}$$

The quality factor must also be  $>77$  after tuning and is given by:

$$Q = \frac{1\text{MHz } 2\pi L_s}{R} \tag{10}$$

where  $R$  is the resistance of the coil. Table 3 below shows data calculated for the circuit modeling.

### C) PTE simulations

Figure 5(a) shows the circuit schematic of the modeled wireless power system while Fig. 5(b) shows the ADS schematic of the system. This simulation model is expanded on and based on the reported findings from [70]. The source is an oscillator

which generates the AC signal at 100 kHz that flows into the transmitter coil,  $L_p$  generates an oscillating magnetic field,  $C_p$  is the resonant capacitor calculated from equation (8) that generates a resonance for  $L_p$  with a coil resistance of  $R$  equation (10). Through the mutual induction tool from ADS, energy from the magnetic field induces AC current in the receiver coil,  $L_s$ .

At the receiver the conventional bridge diodes made of Schottky diodes, convert the signal to DC.  $C_s$  is the series resonant capacitor calculated in equation (8) while  $C_{sp}$  is the parallel resonant capacitor calculated in equation (9) for the receiver coil under test. This receiver model is based on the Qi specification in [63] for type A5.

Figure 6 shows the rectified voltage of a 15 Ω load to be between 6.7 and 7 V. The current is between 500 mA (0.5 A) and 460 mA (0.46 A). The output power was tabulated for a load resistance ranging from 3 to 200 Ω.

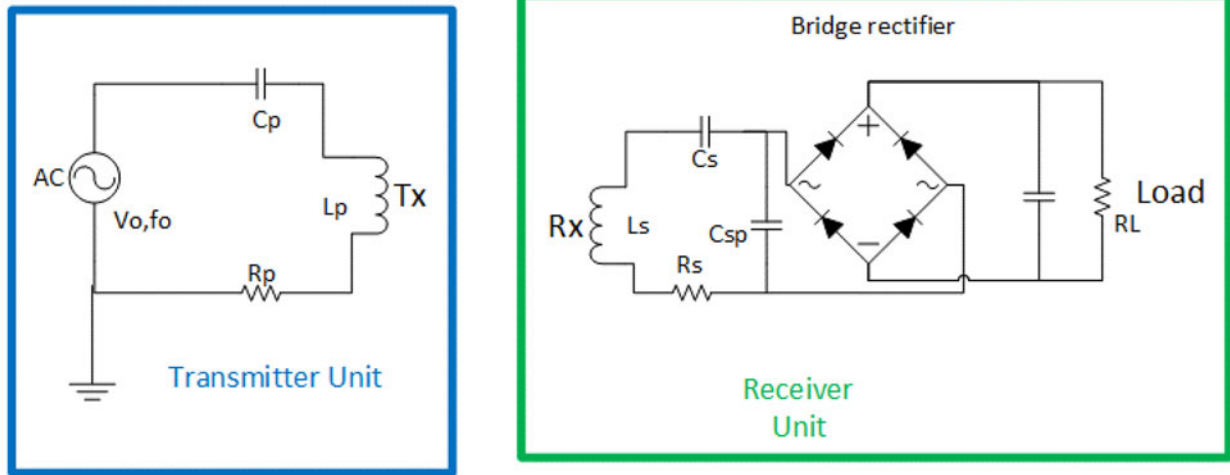
The lithium ion battery used in our system has a high resistance at full charge. Also, to measure the impedance, a battery must be at least 50% charged in practice. A completely drained or nearly empty battery has a high internal resistance. As the battery reaches 50% state-of-charge (SOC), the resistance drops and then increases again towards full charge [60]. Table 4

Table 2. Relevant parameter for selected transmitter and receiver units.

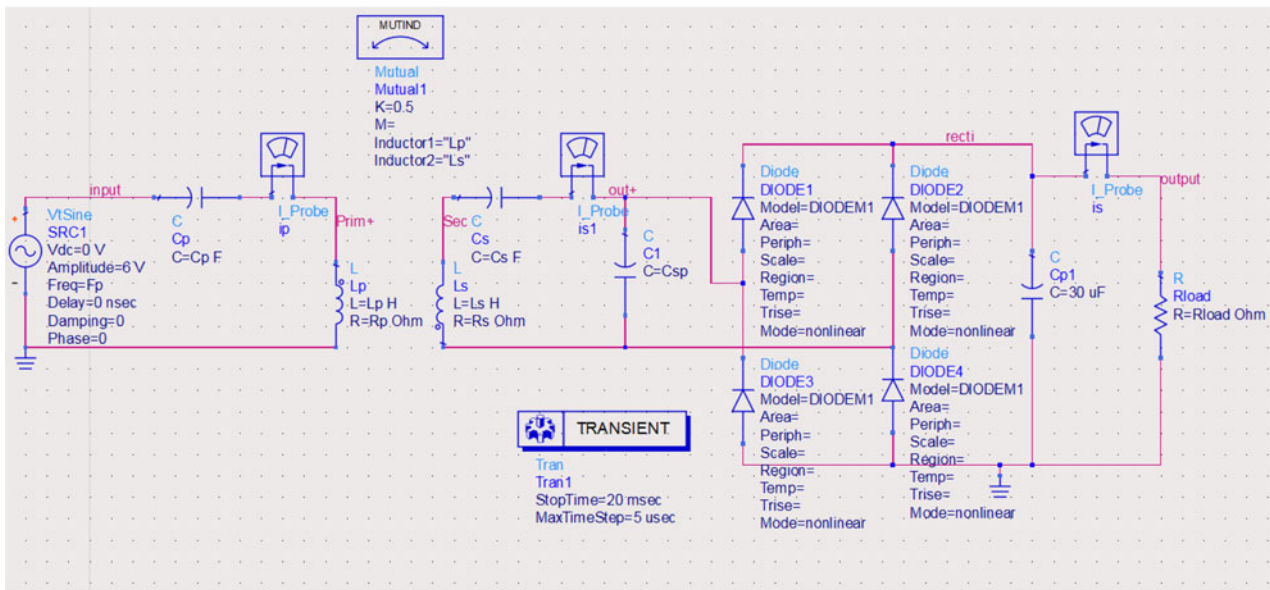
| Transmitter                         | BQ500215EVM-648         |
|-------------------------------------|-------------------------|
| Power supply                        | AC 100~240 V (50/60 Hz) |
| Nominal Vin                         | 11.5–12 V               |
| Rated output                        | 7 V, 10 W               |
| Estimated overall system efficiency | 80                      |
| Operating frequency                 | 100–205 kHz             |
| Receiver                            | 595-BQ51025EVM-649      |
| Max Vin                             | 20 V                    |
| Rated output                        | 4.5–10 V, 10 W          |
| Estimated overall system efficiency | 80                      |
| Operating frequency                 | 100–205 kHz             |

Table 3. Data for simulation setup.

|   | Transmitter             | Receiver                 |
|---|-------------------------|--------------------------|
| Self-Inductance ( $\mu\text{H}$ )         | 10                      | 15                       |
| Coil impedance (Ohm)                      | 0.174                   | 0.157                    |
| Quality factor                            | 90                      | 60                       |
| Coupling factor                           | 0.59                    | 0.59                     |
| Primary resonant capacitor, $C_p$ (F)     | $1.0132 \times 10^{-7}$ | N/A                      |
| Series resonant capacitor, $C_s$ (F)      | N/A                     | $5.3052 \times 10^{-8}$  |
| Parallel resonant capacitor, $C_{sp}$ (F) | N/A                     | $1.3438 \times 10^{-23}$ |
| Source voltage, $V_o$ (V)                 | 5                       | N/A                      |
| Load impedance, $Z_L$ ( $\Omega$ )        | N/A                     | 3–200                    |



(a)



(b)

Fig. 5. (a) Circuitry of the receiver and single coil transmitter units. (b) ADS simulation model illustrating receiver circuit and the single coil transmitter.

shows the output efficiency of the system when charging the battery for increasing resistance as SOC increases towards full charge at 200 Ω. At a low charge, the system has higher and over time the efficiency drops as the battery continues to charge.

### D) Misalignment calculations

Simulations for different alignment conditions were done in MATLAB using equation (22) from [71]. The translational misalignment,  $d_{tm}$  was simulated at a varying distance of separation,  $d_r$ , between the coils as shown in Fig. 7.

Figure 8 shows the plotted power efficiency against a changing transition misalignment,  $d_{tm}$  going from 0 to 7 cm at a varying distance of separation,  $d_r$ , ranging from 0 to 4 cm. The simulations suggest high coupling at smaller  $d_{tm}$  and  $d_r$  distances and tend to zero as the coils are further separated as a result of a lowered coupling factor. The analysis suggests that a misalignment up to about 3 cm will not affect the

performance of the proposed system (since PTE is well above 10%) as this is usually the normal sitting position of the user.

## V. EXPERIMENTAL PROCEDURE

The amount of power transferred with the system varied depending on the load resistance connected to the receiver. Moreover, a range of dummy loads was tested to understand the battery’s impedance since the battery’s charging and discharging activity is a chemical process.

### A) WPT efficiency

The first test procedure is to carry out measurements to determine the power efficiency of the WPT system. The connection was done between the wireless power system consisting of a

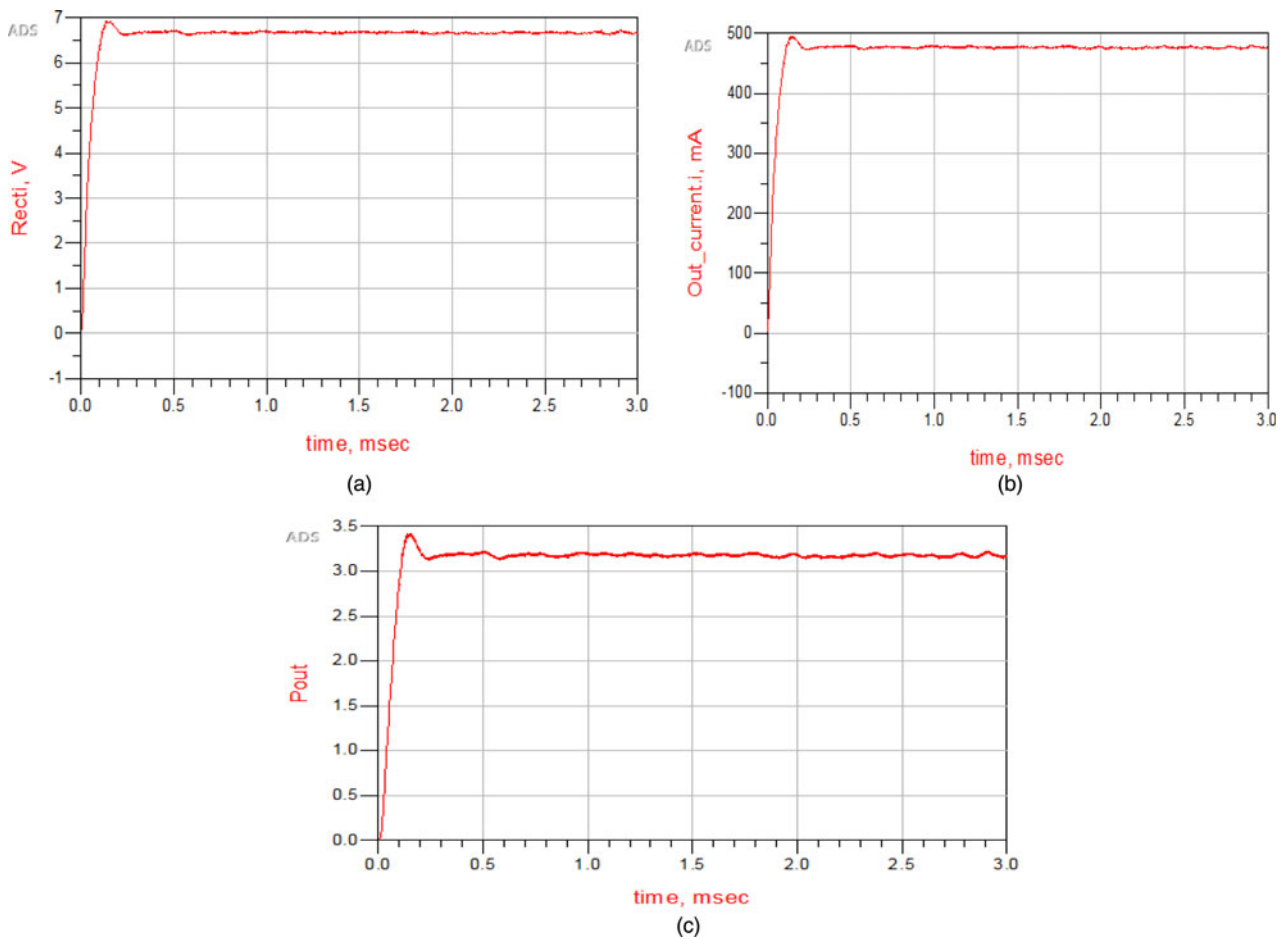


Fig. 6. ADS simulation results at 15 Ω: (a) voltage, (b) current, and (c) power.

dummy load, a receiver and transmitter. The methods, steps, and relevant documentation are described in [66]. These steps serve as a precaution against wrong connections which could lead to components blowing up.

**B) Three-Element Array**

The next step was to replace the single coil with an array of three overlapping coils; i.e. a 3 × 1 array. The coils overlap each other to achieve uniform distribution of the magnetic field, without fields canceling each other [39]. The 3-coil

array is the 760308106 wireless charging coil from Würth Electronic made of ferrite core material. The middle coil has an inductance of 11.5 and 12.5 μH for the side coils. The coils were connected in parallel to the transmitter and tested with the receiver without the battery, as described in Fig. 9.

Table 4. Output result from simulation.

| Load (Ω) | Output voltage (V) | Output current (A) | Power out (W) | Power in (W) | Efficiency (%) |
|----------|--------------------|--------------------|---------------|--------------|----------------|
| 5        | 6.54               | 1.34               | 8.7636        | 11           | 79.7           |
| 7        | 6.63               | 0.91               | 6.0333        | 7.7          | 78.4           |
| 10       | 6.69               | 0.6                | 4.014         | 5.2          | 77.2           |
| 15       | 6.8                | 0.47               | 3.19          | 4.2          | 77             |
| 20       | 7.11               | 0.35               | 2.53          | 3.5          | 72.4           |
| 25       | 7.31               | 0.29               | 2.14          | 3            | 71             |
| 50       | 7.64               | 0.15               | 1.169         | 1.92         | 61             |
| 75       | 7.64               | 0.10               | 0.78          | 1.65         | 47             |
| 100      | 7.72               | 0.07               | 0.59          | 1.44         | 41             |
| 200      | 7.77               | 0.03               | 0.30          | 1.32         | 22             |

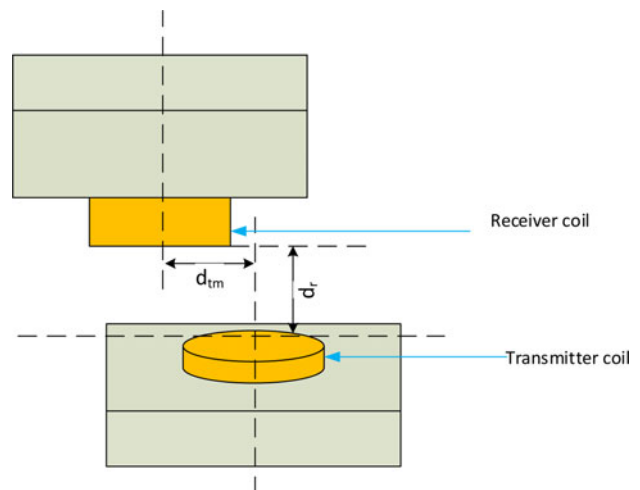


Fig. 7. Basic configuration of translational misalignment between the coils.

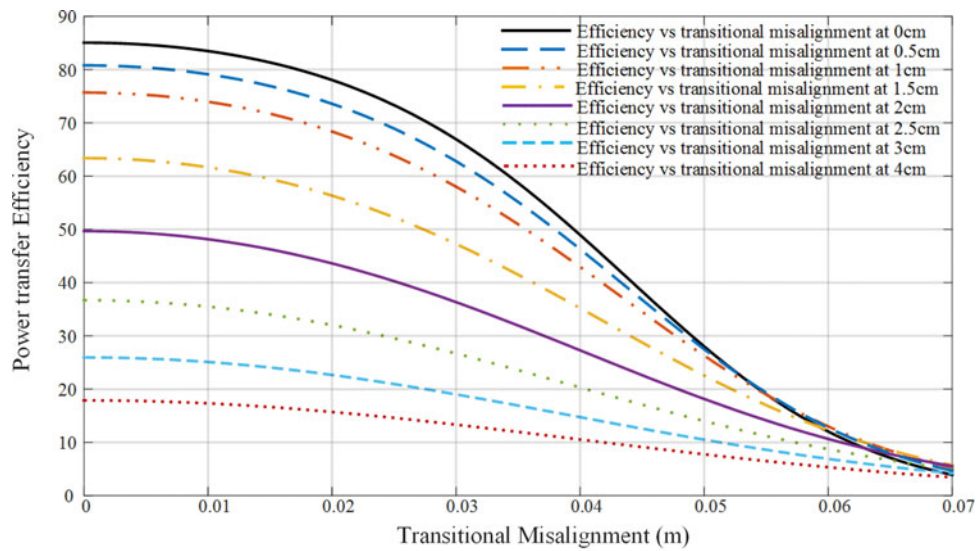


Fig. 8. Power transfer efficiency at different misalignment positions shown in Fig. 7 by varying the distance between the transmitter and receiver coils in x and y directions.

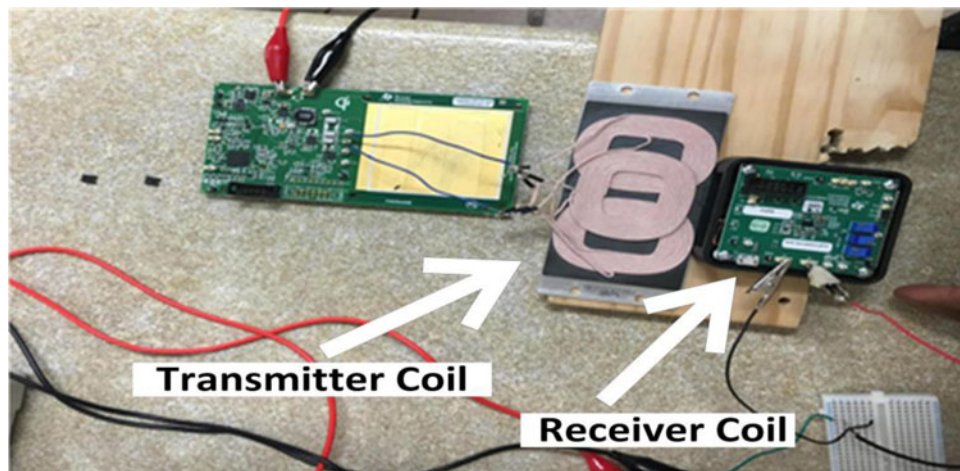


Fig. 9. Single transmitter coil replaced by the 3 × 1 array.

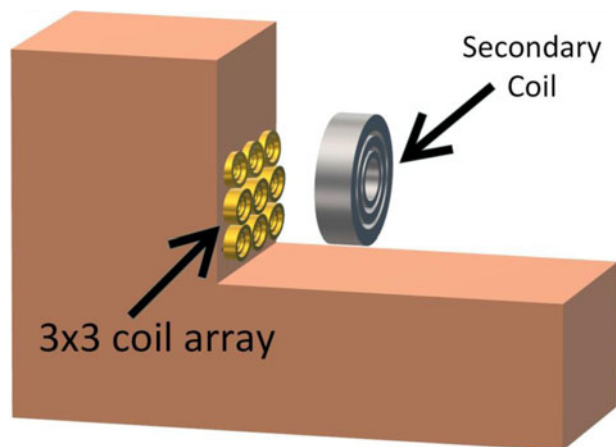


Fig. 10. Model illustrating the primary coil arrangement in the backrest.

C) 3 × 3 Coil array

In this set-up a couple of rows were added to the 3 × 1 array (as described above) to increase the free positioning range on the backrest. Only the primary coils next to the receiver activated the power transfer process. This coil arrangement was made of three single 3 × 1 coil array resulting in a 3 × 3 coil arrangement array as described in Fig. 10.

VI. EXPERIMENTAL RESULTS

A) WPT efficiency measurement

The wireless PTE of the system was calculated by measuring the input power at the transmitter and the output power at the receiver as expressed by:  $\eta = P_{RX}/P_{TX} \cdot 100\%$ , where  $\eta$  is the efficiency,  $P_{RX}$  is the output power in watts and  $P_{TX}$



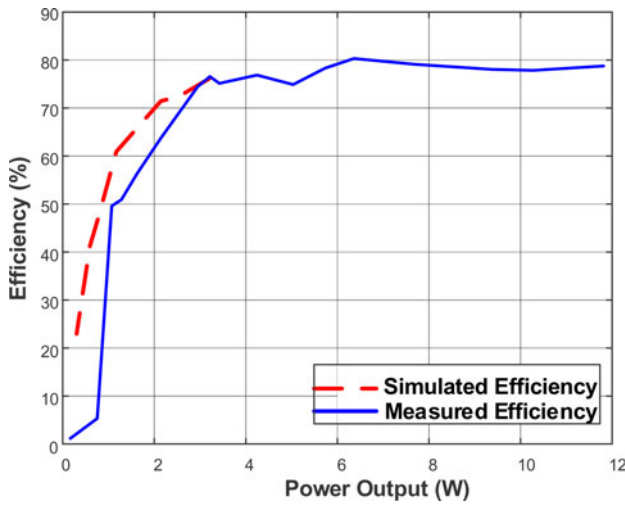


Fig. 11. Measured and simulated efficiency.

is the input power in watts. The efficiency of the system went up to 80% and decreased as the load resistance increased.

Figure 11 shows the efficiency plot of the simulated and measured device. From this plot we are certain the WPT system works properly.

**B) Power measurement**

An open circuit test was done to estimate the batteries SOC, which is the maximum possible charge inside a battery at

Table 5. Open-circuit measurement using industrial charger.

| Charger voltage (V) | Charger current (A) | Time (hrs) | Voltage per Cell (V/cell) | Estimated saturation capacity (%) |
|---------------------|---------------------|------------|---------------------------|-----------------------------------|
| 8.79                | 0.63                | 0.5        | 0                         | 0                                 |
| 8.79                | 0.63                | 1          | 2.9                       | 69                                |
| 8.79                | 0.63                | 1.5        | 3.4                       | 80.9                              |
| 8.79                | 0.63                | 2          | 3.51                      | 83.5                              |
| 8.79                | 0.63                | 2.5        | 3.57                      | 85                                |
| 9.56                | 0.38                | 3          | 3.9                       | 92                                |

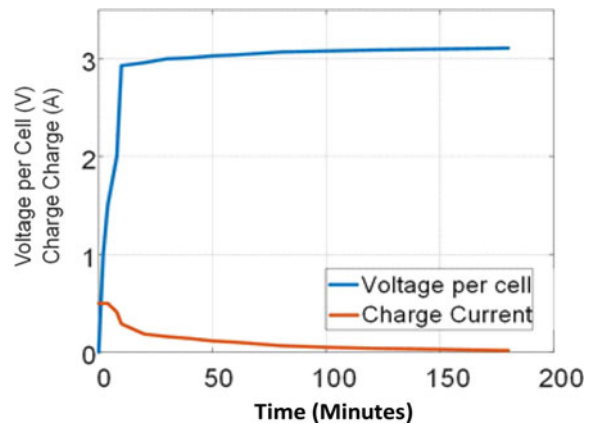


Fig. 13. Voltage-current curve of wireless power system and battery pack.

Table 6. Discharge result of battery.

| Industrial charger |             |             | WPT system |             |             |
|--------------------|-------------|-------------|------------|-------------|-------------|
| Time (hrs)         | Voltage (V) | Current (A) | Time (hrs) | Voltage (V) | Current (A) |
| 0                  | 7.49        | 0.64        | 0          | 7           | 0.46        |
| 0.5                | 7.4         | 0.626       | 1          | 6.8         | 0.43        |
| 1                  | 7.04        | 0.61        | 2          | 6.08        | 0.42        |
| 2                  | 6.8         | 0.58        | 2.5        | 5.8         | 0.39        |
| 3                  | 6.3         | 0.56        |            |             |             |
| 4                  | 6.2         | 0.53        |            |             |             |
| 5                  | 5.9         | 0.5         |            |             |             |

any one time. It mainly involves measuring the two terminals of a battery in open-circuit as described in [72] to obtain the voltage per cell. The battery was charged using an industrial charger and results from this were compared to the charging process done by the wireless power system, shown in Table 5, Fig. 12.

When the battery starts to charge, the voltage starts to rise quickly while the current is constant and then when charging progresses towards saturation, the current starts to drop while the voltage remains constant until terminated at stage 3. Meanwhile the charge capacity increases as shown in Fig. 13.

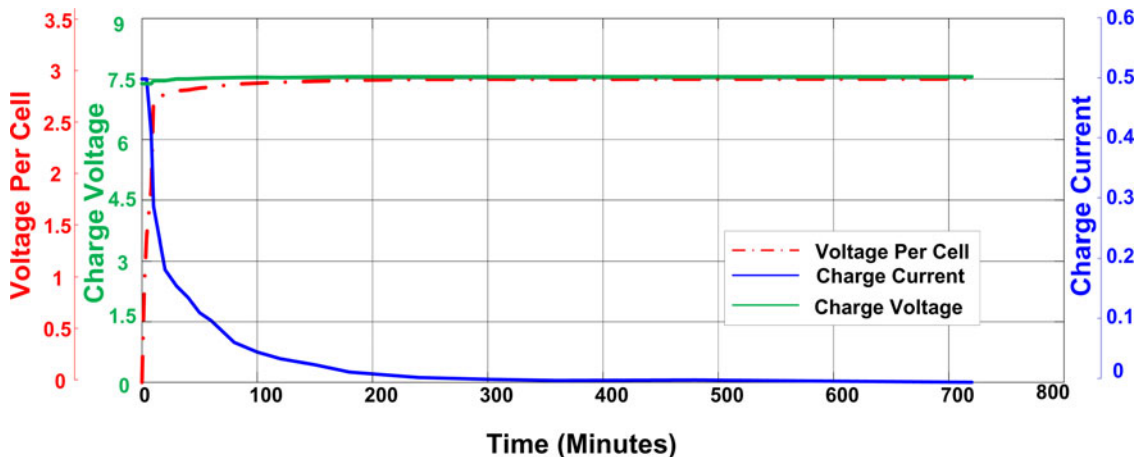


Fig. 12. Open-circuit measurements using WPT system.

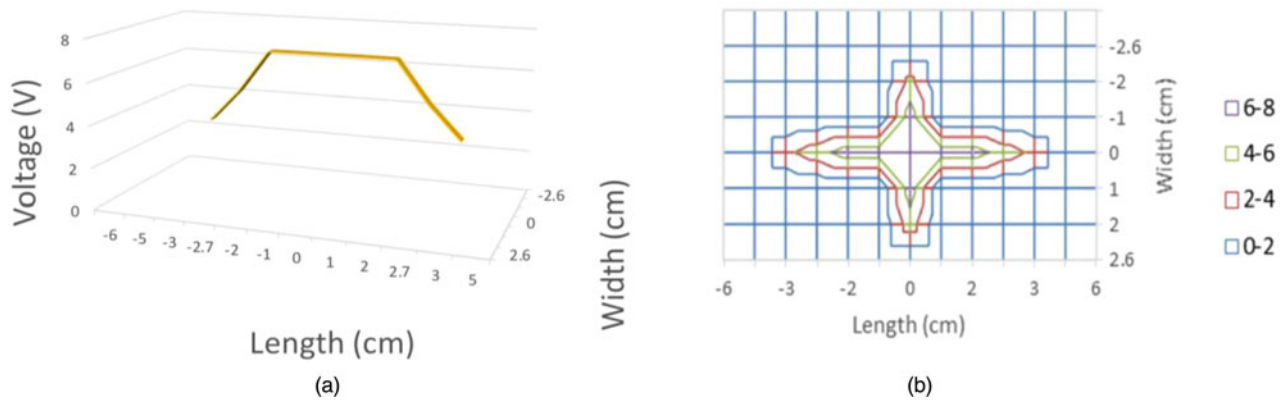


Fig. 14. Measured induced voltage in the secondary coil for the 3 × 1 array. (a) 3D representation, (b) contour plot representation.

Table 7. Alignment results.

|                                  | Single coil                 |             | 3-Coil Array                 |             |
|----------------------------------|-----------------------------|-------------|------------------------------|-------------|
| Model                            | 760308141(Wurth Electronic) |             | 760308106 (Wurth Electronic) |             |
| Inductance ( $\mu$ H)            | 10                          |             | 12.5, 11.5, 12.5             |             |
| Resonance frequency (MHz)        | 11                          |             | 14                           |             |
| Operating Area ( $\text{cm}^2$ ) | 1.56                        |             | 20                           |             |
|                                  | Displacement (cm)           | Voltage (V) | Displacement (cm)            | Voltage (V) |
| Ideal Position                   | 0                           | 7.05        | 0                            | 7.08        |
| X-axis                           | 2.4                         | 7.01        | 10.6                         | 6.96        |
| Y-axis                           | 2.6                         | 7.02        | 2.7                          | 5.1         |
| Z-axis                           | 2.2                         | 6.99        | 3                            | 4.96        |

C) Discharge testing

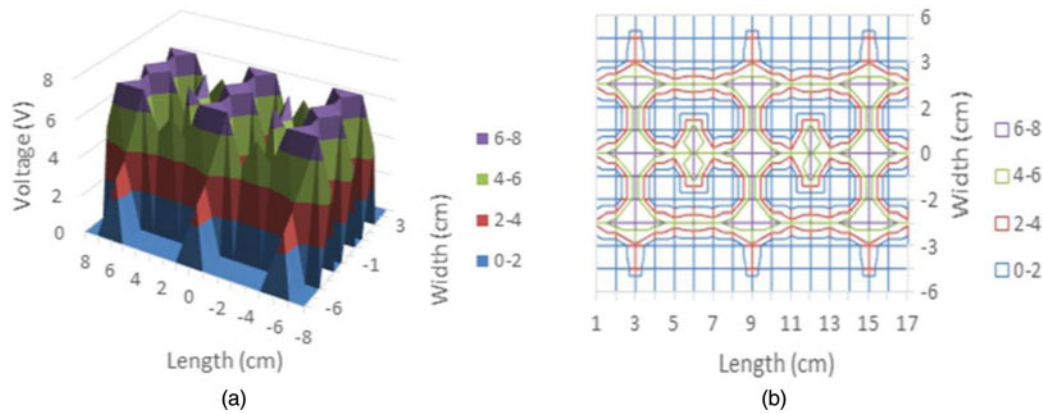
It was observed the custom-made battery pack was able to regulate the current going into it. This safety feature was necessary as the battery was used to power a wearable and textile-based commercial product. This led to the significant

drop of charge current as compared to the charger which employs a voltage regulator circuitry.

The WPT system cannot raise the voltage per cell higher as the charge current becomes too low resulting in lower saturation which can lead to a lower discharge time of 2.5 h compared to 5 h seen when the battery reaches a higher capacity



Fig. 15. The 3 × 3 coil array structure.



**Fig. 16.** Measured induced voltage in the secondary coil for the  $3 \times 3$  array. (a) 3D representation, (b) contour plot. These plots indicate the considerably larger area for the WPT coverage when the  $3 \times 3$  array of coils is used.

from the use of an industrial charger. Table 6 shows the voltage discharged after 3 hours when charged with the original charger and WPT system.

#### D) Alignment testing

One of the main issues of concern is the systems flexibility particularly relating to alignment. Coupling should occur at any part of the system regardless of the sitting position. A possible solution is the use of an array of coils at the transmitter. The single transmitter coil was replaced by a 3-coil array as shown in Fig. 14, Table 7.

#### VII. $3 \times 3$ COIL ARRAY IMPLEMENTATION

The voltage induced at the secondary coil using a  $3 \times 3$  primary coil array was compared to that of a primary  $3 \times 1$  coil array as shown in Figs 14 and 16, this was done to determine the dependence of the flux linkage. The primary coil array was connected in such a way to have an approximate inductance value of 10  $\mu\text{H}$  as specified in [66]. The inner diameter and outer diameter of a single coil element within the array was 44.8 and 15.5 mm, respectively. It has 13 turns and a wire diameter of 1.19 mm. The gap between coils within the array was 1.85 mm and a single  $3 \times 1$  array (3 elements) has a dimension of 94.7 mm  $\times$  53.35 mm while the complete  $3 \times 3$  array (9 elements) is 94.7 mm  $\times$  162 mm.

The  $3 \times 3$  array was found to have an increased coverage area of 187  $\text{cm}^2$  from that of 28.62  $\text{cm}^2$ . Figure 14(b) shows the coverage area as a function of voltage recorded for the  $3 \times 1$  array, the concentration, and charge area is seen to have increased in Fig. 16(b). The induced voltage at the receiver was measured by moving the coil center at grid intervals of 17 cm  $\times$  11 cm and spaced at 1 cm apart. A similar technique was used in [73]. Fig. 15 shows the coil arrangement under the charge area.

High and low peaks for the induced voltage can be observed in Fig. 16. The presence of low peaks indicates a low charge area due to the fact that the coil array elements do not completely overlap each other or are not completely close enough to ensure uniform coverage. Thus, improvements in the transfer efficiency could be possible by using a more compact array.

#### VIII. CONCLUSION AND FUTURE WORK

A WPT system was designed for a novel wearable heating system that provides warmth to its user. The wireless system consists of an array of coils at the transmitter and a single coil receiver that powers polymer resistors that generate heat when driven by applied current. This provides comfort and heat therapy for the wearer of the belt. The flux distribution was also investigated among two array configurations by moving the receiver across the array surfaces and recording the induced voltage. This helped determine the alignment conditions of the set of the arrays to achieve a considerable area of operation. Results in the paper demonstrated that a significantly increased charge area was made possible by the employed  $3 \times 3$  coil array. Further improvements for the system can be made by designing an accompanying voltage regulator integrated circuit such as LM317 (variable regulator) or any fixed regulator such as LM7808 or LM7812 for better output voltage stability.

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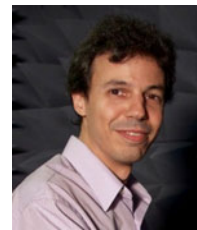
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