A Wireless Power Charger System using a 2-D Near-Field Array for Assisted Living Applications

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Abstract— Wireless power transfer (WPT) can enable connector-free systems that do not rely on more conventional wired connections. In this paper, a wireless battery charger for a wearable body heater, where the transmitting system is integrated into a chair, is reported for benefiting assisted living residents. This system incorporates the widely adopted Qi wireless charging standard that is accepted by industry. Alignment conditions between a 3×1 and a 3×3 coil matrix array are investigated in the form of the voltage induced in the secondary coil. The results of this work, when compared to more conventional single coil systems, is the extended charging area for its users enabling more efficient WPT and beneficial heating in the near-field. For example, the proposed 3×3 coil array was found to have an increased charging area of 187 cm² from that of 28.62 cm² for the 3×1 coil array. To the best knowledge of the authors no similar wearable WPT system has been reported for assisted living applications and wireless heating.

Index Terms — Ambient assisted living, wireless power transfer, Qi standard, transitional misalignment.

I. Introduction

With the average life expectancy in Europe and industrialized countries increasing, there are societal and economic consequences, ranging from new pension and taxation systems, and further strains on the health care system. In an effort to reduce government spending costs particularly in the health sector and respond to these changes, schemes are being promoted to find technical solutions to allow older adults to continue living independently while mitigating the economic consequences of the increasing elderly population and also creating business opportunities for start-up companies [1, 2].

A particular area of increased interest is Ambient Assisted Living (AAL). AAL consists of the use of smart systems with humanistic intelligence enabling and supporting the elderly and special needs individuals. The primary consideration of these systems is to improve lives by increasing the safety, comfort and independence of residents' lifestyles in their immediate environments. These efforts are achieved by involving those residents and their caregivers in the development stage of such system design using innovative and cost-effective solutions. AAL systems usually involve health management, overall body monitoring, assisted mobility, social interactions, and security [3, 4].

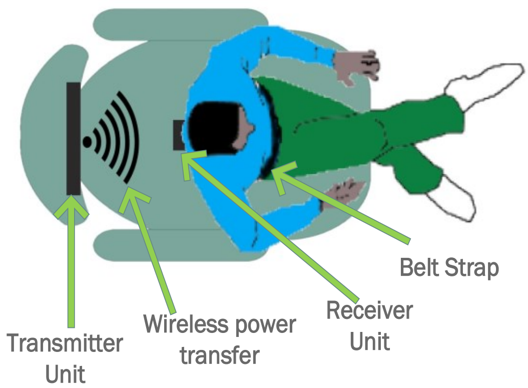


Fig. 1. Setup showing the working concept of the wireless power transfer (WPT) system when the user is sitting in the chair.

This work describes a wireless and an AAL solution, which consists of the integrated functionality of a novel far-infrared heating element for body warming. Smart features using the Internet of Things (IoT) approaches can also be implemented to help regulate body temperature. It is intended to benefit assisted living residents who are suffering from dementia and Alzheimer's, and who are not able to do basic tasks such as keeping themselves warm during low temperature conditions like in the winter periods. The wearable technology can also have a GPS navigation system to track dementia patients who randomly wander about causing panic for their caregivers and family members.

Our approach is based on the Qi WPC wireless power standard that was established to provide interoperability between transmitters and receivers. The Qi WPC standard has experienced much change in the past few years with more variety of wireless chargers becoming prevalent. The main applications for these chargers are desktop chargers, power banks, and embedded chargers. Moreover, desktop chargers generally consist of a charger while embedded chargers can be built into furniture, automobiles, and other appliances. Also, the growth of Qi wireless devices and chargers is becoming more publicized as more products and applications emerge, with the advantage of reducing the need for product-specific cables and reducing frequent failure of the device's charging connector.

Our research reported in this paper involves designing a Wireless Power Transfer (WPT) system to power a belt which uses textile materials to provide body heating to its user as illustrated in Fig. 1. It also involves analyzing the alignment and power conditions of the charging area on the seat backrest using arrangements with a single coil and with multiple coils [5]. The major constraint in the system is the distance and any misalignment, since WPT is an Inductive Power Transfer (IPT) based system. This is because the belt must be near the backrest of the chair as shown in Fig. 1 as power transfer is expected to occur at any sitting position. The proposed solution is to have an array of coils embedded at the chair backrest for an increased coverage area and thus offering an improvement in the transfer efficiency.

This solution follows earlier concepts from [6], where several primary coils were placed beneath a desk surface to supply power to portable equipment placed on top of the desk. Only the primary and the secondary coils facing each other work to activate the power transfer process.

II. POWER SYSTEM

The proposed WPT system is made up of the functional belt fabric, which is worn by the user that includes the heating material, a battery pack and a wireless power receiver. The chair backrest houses the wireless power transmitter. The belt is made up of a wireless receiver and battery along with a Far Infrared (FIR) heating element which is sewn into it. FIR is a form of infrared best used as a therapy to accelerate the recovery of muscles and can reduce pain. Studies suggest that the wavelength of the FIR radiation and vibration frequency characteristics of the human body are closely in sync, this allows the FIR element to release heat and penetrate the skin to the muscles, blood vessels, lymphatic glands and nerves when warmed [7]. When considering our proposed WPT system, assisted living residents will benefit since charging is done wirelessly, as compared to more conventional heating systems which are typically wired.

The chair houses the wireless transmitter that is powered from the mains. The power transfer and communication protocol of the system follows the Qi WPC standard that uses inductive coupling at the resonance frequency. The transmitter converts and transmits an AC power signal to the receiver, where it is rectified generating a DC voltage. Power control is done by the transmitter side and the transmitter modifies the signal frequency in the 100 kHz range and its duty cycle is in the 10% to 50% range. Whenever the power level required by the receiver is increased, the transmitter dynamically reduces the frequency down to 100 kHz. The recommended distance between the transmitter and receiver coils range from 2 cm to 5 cm [8].

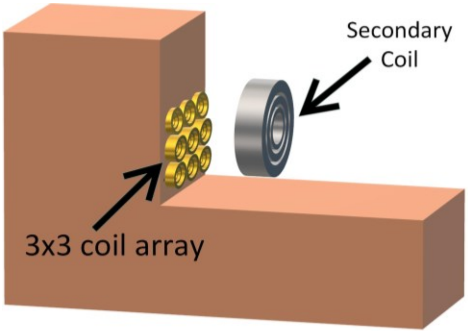


Fig. 2. Illustrative model showing the primary coil arrangement in the backrest of the chair. The secondary coil would be integrated within the user's belt.

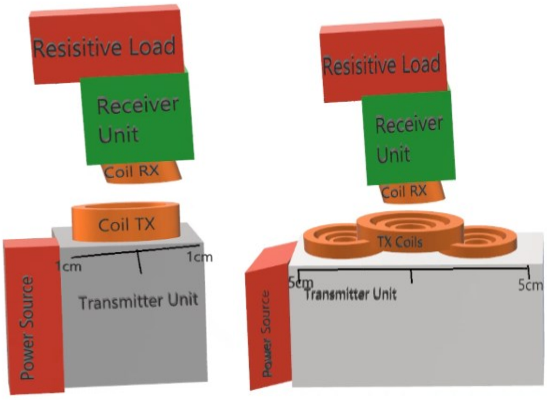


Fig. 3. Representation of the single coil transmitter unit and an array of 3x1 transmitter coils.

III. MODELLING AND SIMULATION

A circuit model of the wireless power system was made using the Keysight ADS simulation tool based on [8]. Fig. 4 shows the simulation model to obtain the power output at the receiver (based on the standard in [9]) for any coupling condition using the coil types selected for the chosen application. The transmitter module is made up of an oscillator capable of producing the required resonant frequency, which drives alternating current into the primary coil. The receiver converts the signal to DC through a rectifying circuit [9].

A. Power Transfer Efficiency Simulations

The WPT efficiency of the system was simulated by observing the input power at the transmitter and the output power at the receiver as expressed by:

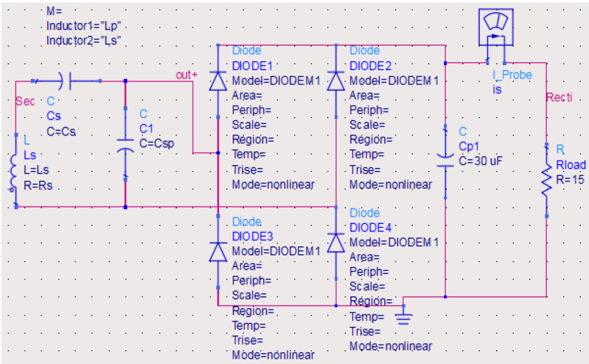
$$\eta = (P_{Rx} / P_{Tx}) \cdot 100 \ \ (\%) \qquad (1)$$

where η is the efficiency, P_{RX} is the output power in watts and P_{TX} is the input power in watts. The efficiency of the system went up to 77% and decreased as the load resistance increased.

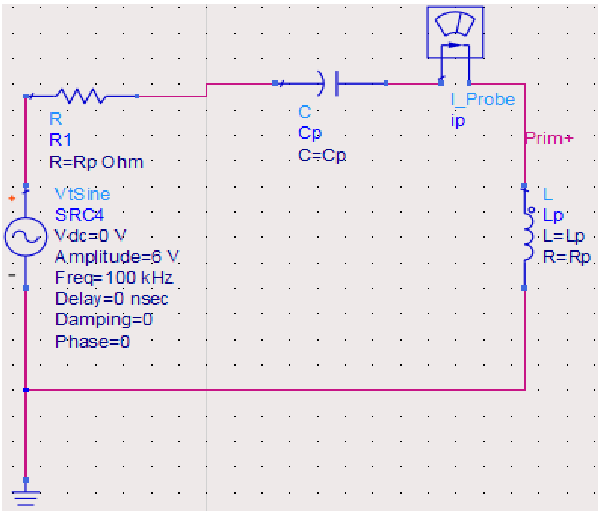
The receiver circuit has two resonant capacitors C_s, a series resonant capacitor and C_{sp}, a parallel resonant capacitor, as further described in [8]. The capacitors C_s and

C_{sp} along with the receiver coil make up a dual resonant circuit. The two capacitors are used to tune the receiver coil following the Qi standard and should be sized correctly based on the Qi specification [9], where the Rx coil is then placed on the spacer, and L_{rx} is measured with a stimulus of 1 V RMS. All values for the circuit elements in the simulation model are further defined in Table 1.

Fig. 4 shows the circuit schematic of the modelled wireless power system. The source is a sine wave oscillator which generates the AC signal at 100 kHz that flows into the transmitter coil of 10 uH which generates an oscillating magnetic field. Through mutual induction, energy from the magnetic field induces an AC current in the 15 uH receiver coil. At the receiver, the bridge diodes convert the signal back to DC. Fig. 5 shows the rectified voltage for a 15 Ω load. The current is between 750 mA and 800 mA. The output power was tabulated for the load resistance ranging from 15 to 50 Ω. It should also be mentioned that this receiver model is based on the Qi specification in [5] for type A5.

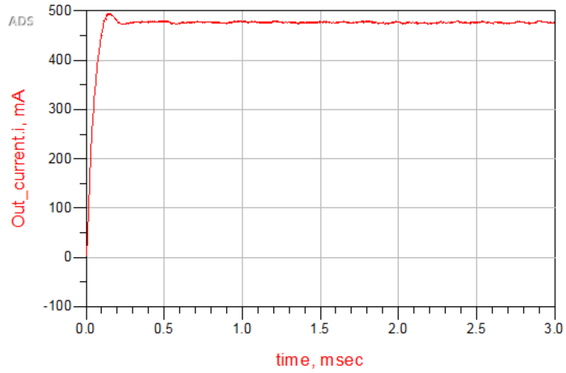


(a)

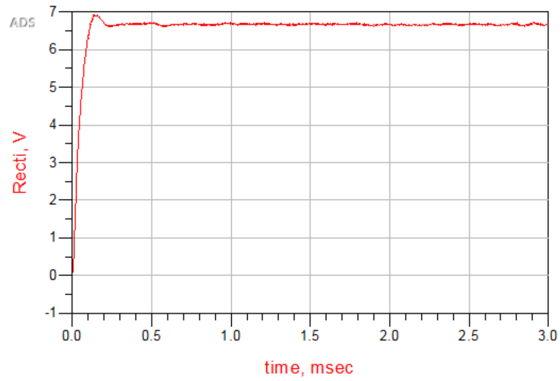


(b)

Fig. 4. Simulation model illustrating (a) the receiver circuit in ADS and (b) the single coil transmitter circuit in ADS.



(a)



(b)

Fig. 5. ADS simulation result at 15 Ω for the (a) current and (b) the voltage at the receiver.

Table 1. Data for the ADS Simulation Setup

Circuit Parameter	**Tx**	**Rx**
Self-Inductance (μH)	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)	$1.01 \cdot 10^{-7}$	N/A
Series resonant capacitor, C_s (F)	N/A	$5.3 \cdot 10^{-8}$
Parallel resonant capacitor, C_{sp} (F)	N/A	1.3e-23
Source Voltage, V_o(V)	5	N/A
Load Impedance, R_L (Ω)	N/A	15 to 200

B. Power Transfer Efficiency Measurements

The efficiency test procedure was carried out to determine the power efficiency of the wireless network. The connection was done between the wireless power system consisting of a dummy load, a receiver and a single coil-transmitter. Similar steps and methods as well as the relevant documentation are described further in [10]. The WPT efficiency of the system was calculated by measuring the input power at the transmitter and the output power at the receiver as expressed by (1).

Fig. 6 shows the efficiency plot of the simulated and measured device. From this plot we are certain the WPT system works properly. For an internal resistance of 50 Ω, the battery has an efficiency of 61%. It was observed that the battery is fully charged with an internal resistance of 200 Ω. During charging from a low charge to full charge, the internal resistance starts to rise until it reaches 200 Ω at this load we experience very low efficiency. This is important since the system requires an input power of 3 W to operate properly. Table 2 shows that the system can meet this requirement and power transfer efficiencies greater than 60% are observed. Fig. 7 illustrates the measurement setup using a breadboard connection.

Table 2. Simulation Results.

Load (Ω)	Output Voltage (V)	Output Current (A)	Power Out (W)	Power In (W)	Efficiency (%)
50	7.64	0.15	1.169	1.92	61
25	7.31	0.29	2.14	3	71
20	7.11	0.35	2.53	3.5	72.4
15	6.8	0.47	3.19	4.2	77

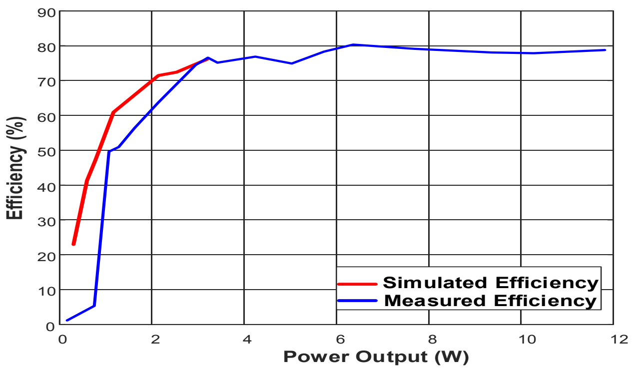


Fig. 6. Comparison of the simulated and measured power transfer efficiency.

C. Misaligment Simulations

Simulations for different alignment conditions were also completed in MATLAB using (22) from [11]. The transitional misalignment, d_{tm} was simulated at a varying distance of separation, d_r between the coils. Fig. 8 shows the plotted power efficiency against a changing transition misalignment, d_{tm} going from 0 cm to 7 cm at a varying distance of separation, d_r ranging from 0 cm to 4 cm. The simulation suggests high coupling at a smaller distance of d_{tm} and d_r tends to zero as the coils are further separated because of reduced coupling values. The analysis shows that a misalignment of up to 3 cm will not affect the performance of the proposed system as this is usually the normal sitting position of the user.

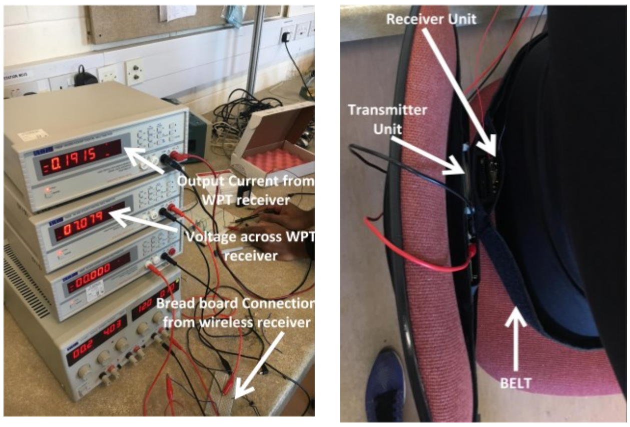


Fig. 7. Measurement equipment and setup (left). The wireless power system operating in the belt and chair (right).

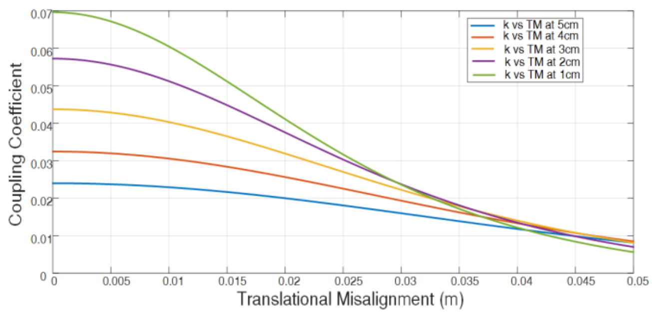


Fig. 8 Coupling coefficient at different misalignment positions shown by varying the distance between the transmitter and receiver coils in the *x* and *y* directions.

D. Coil Array Implementation

Voltage induced at the secondary coil using a single primary coil array was compared to that of a primary 3×1 coil array. This was done to determine the position dependence of the flux linkage and the improvement made possible due to the coil array. Fig. 9 shows the new coil transmitter. The secondary coil array was connected in such a way to have an approximate inductance value of 10 uH as specified in [12].

The 3x1 array was found to have an increased charge area of 28.62 cm^2. Fig. 10 shows the charge area as a function of voltage recorded for the 3×1 array. The induced voltage at the receiver was measured by moving the coil centre at grid intervals of 1 cm. A similar technique was used in [13].

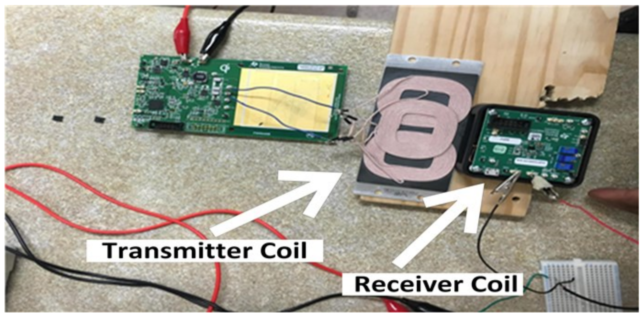


Fig. 9. Setup of a 3x1 array transmitter and the receiver coil.

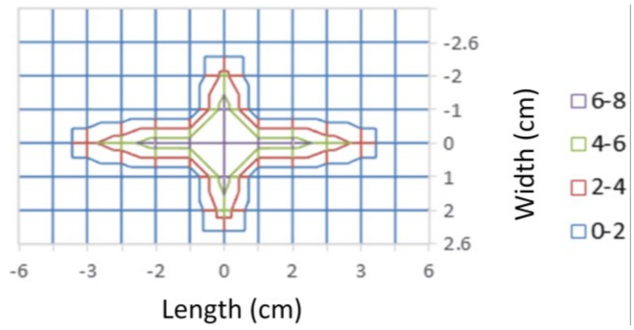


Fig. 10. Measured induced voltage in the secondary coil for the 3×1 array. It can be observed that received voltage values are greater than 2 V for a 6 cm linear range.

Voltage induced at the secondary coil using a 3×3 primary coil array (see Fig. 11) was compared to that of a primary 3×1 coil array and the extended horizontal range. The inner diameter and the outer diameter of the coil elements were 44.8 mm and 15.5 mm, respectively. The individual elements also have 13 turns and a wire diameter of 1.19 mm. The gap between the coils on the arrays is 1.85 mm. The single array has a dimension of 94.7 mm by 53.35 mm and the complete array is 94.7 mm by 162 mm.

The 3×3 array was found to have an increased charge area of 187 cm^2 from that of 28.62 cm^2 for a 3×1 coil array. The induced voltage at the receiver was measured by moving the coil centre at grid intervals of every 1 cm. A similar technique was used in [13] and similar results were reported in [14] and [15]. In our work, it was observed that high and low peaks of the induced voltage, between 2 V and 8 V, were possible. It should also be mentioned that the presence of low voltage values were recorded indicating a low charging efficiency. This was because the elements of the array did not always overlap with each other. Improvements in the transfer efficiency could be possible by using a more compact array.

Fig. 11. The 3×3 coil array structure.

IV. Conclusion

A wireless charging system was designed for a novel wearable heating belt that provides warmth to its user. The system consists of an array of coils at the transmitter and a single coil receiver that powers polymer resistors which generate heat when current is passed through them. Two transmit array configurations were also investigated by moving the receiver across the array surfaces and observing the induced voltage. This is expected to help alignment conditions and ensure more efficient wireless power transfer for battery charging.

V. Acknowledgment

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