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Wireless Power System for Video Capsule Endoscopes: Design, Development, Implementation, and Analysis

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***Abstract* — A tiny capsule called a Video Capsule Endoscope (VCE) is used to diagnose gastrointestinal illnesses. It is a swallowable capsule with a built-in camera, power source, and light source. The inner lining of the small intestine is photographed by the capsule. This area of the intestine is inaccessible to conventional upper endoscopy and colonoscopy. With the help of this technique, polyps, Crohn's disease, ulcers, and small intestine malignancies can all be identified. This capsule's battery life is its main drawback. The typical battery life is 7-8 hours; however, our minimal digestion takes roughly 12 hours. This paper offers a solution to the issue of the power deficit. We use a wireless means to power the VCE following our method. The VCE's electronic components consume about 100mW of power. Inductive magnetic coupling is used, in which the transmitting circuit generates a magnetic field, and the receiving circuit, located inside the VCE, receives AC power by electromagnetic induction. The AC power is changed into DC power, which provides the VCE with the energy required to complete the process.**

***Keywords* — Video Capsule Endoscope (VCE), WCEs, Wireless Power Transfer.**

I. INTRODUCTION

Most diseases, including ulcers and tumors, are curable or treatable in the early stages, or else they develop into malignant growths or other basic disorders. Although it is challenging, early diagnosis of many disorders is crucial. Numerous indirect technologies, including angiography, ultrasonography, X-radiography (including CT), and scintigraphy, have been developed to detect Gastrointestinal (GI) tract disorders [1]. Endoscopy is a quick and effective symptomatic innovation because directly observing the GI tract is the best way to detect GI infections and reveal the internal tracts [2]. The development of wired endoscopy made it possible to view the colon, upper small intestine, and entire stomach [3]. Endoscopy is now the accepted method and the accepted standard for diagnosing gastrointestinal tracts because it enables clinicians to see the GI system [4], [5].

In conclusion, endoscopy is a non-surgical process used to observe someone's digestive system. An endoscope is a flexible tube with a connected light and camera that can take pictures of the gastrointestinal tract and digestive tract for a doctor to examine. The conventional endoscope's wireless variant debuted back in 2001. Video capsule endoscopy also referred to as VCE or WCE (Wireless Capsule Endoscopy), is the current name for this [6]. The WCE framework establishes four subsections including the wireless power supply section, the central processing unit, the data transmission system, and the imaging system. The overall size of the VCE is small enough to be swallowed by patients without any problem [7]. During its movement through the GI tract with the peristalsis, the CE pictures the GI tract. The pictures are transmitted remotely outside of the patient's body and get by the accepting box which is attached to the patient's abdomen. The WCE is fueled by a cell battery, which can keep working constantly for as long as 6-7 hours [6]. But the normal digestion of the human body takes at least 12+ hours and can last a couple of days. So, a certain part of the GI tract remains unexamined. Olympus Pill cam's imaging quality is about 2-8 frames/second, and its resolution is about 256*256 [8]. The challenge is to improve the frame rate as well as the quality of the images taken by the capsule. But increasing the image quality means new image compression algorithms [9]. Implementing this algorithm required more power than the battery cells can supply. shows a conventional VCE with batteries [10].

As a solution to this problem, Wireless Power Transmission is used. In this paper, a wireless power supply system has been analyzed and implemented that will power the WCE (Wireless Capsule Endoscope)/VCE wirelessly from an external source. Various methods can be followed to obtain this power transmission and each of the methods comes with its drawback and limitations. In this paper, we try to find the optimum solution to the problem which is overcoming the primary challenges of traditional wireless capsule endoscopy. After analyzing the issue with battery-powered endoscopy capsules, we determine various technologies and methodologies by which power can be transferred to the capsule in a wireless medium. The primary design of wireless power systems has been discussed. The design includes 4 key parts. A wireless power transmission (WPT) device, 3D wireless power receiving device, a Video capsule endoscope, and a workstation. This research analyzes the design and development aspect of both power transmission and receiving coils, transmitting circuit, resonant frequency in the transmission of power and efficiency of transmission of each design solution.

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After many simulations and following different methodologies for wireless power transfer, we designed and implemented the optimum solution in the laboratory. In terms of the power transfer section, a Helmholtz coil configuration was used, and a class D power amplifier circuit was used for power amplification. In the case of the power receiving section, a 3D-modeled receiving coil was implemented and connected to a receiving circuit which is responsible for power stability of the power coming to the receiving end which is the capsule itself. In our experiment, we were able to transfer a maximum power of 147 mW through a wireless medium to the VCE. The minimum power received at the worst condition of positioning is 88 mW.

Fig. 1. A conventional VCE with batteries.

II. SYSTEM OVERVIEW

A. VCE Architecture

The Video Capsule is the main unit of the whole system. The pill-sized capsule includes multiple subsections such as the CMOS imaging system, LED lights, Image processing and compressing unit, data/image transfer unit, and power unit.

The 3D structure of the capsule and wireless coil powered VCE can be seen in Fig. 2 and 3. In Fig. 2, we can see the numbered subsections of a capsule. The LED lights which are necessary for taking bright images of the intestinal tract can be seen in the far left of the image depicted by 1. The other sections are the CMOS imaging sensor at number 2, the power regulating circuit at number 3, the antenna at number 4, and the wireless power receiving circuit at number 5. The number 6 is the antenna for wireless communication and the final subsection depicted by the number 7 is the receiving coils.

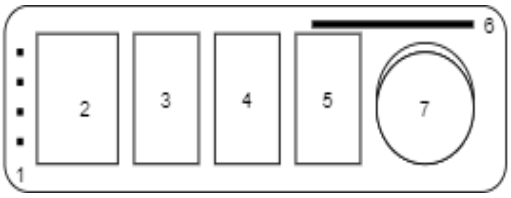


Fig. 2. The architecture of Wirelessly Powered VCE.

The whole system is enclosed in a transparent plastic capsule. The LED light is used for illumination inside the GI tract. The CMOS (Complementary metal oxide semiconductor) is the main imaging sensor; for taking the picture at a pre-defined frame rate which is then processed and compressed by the image processing unit. The CMOS sensor has a field of view of 70º and can take pictures up to 30 frames per second. The image processed by the main processing unit is transferred by the data transmission system to a working station monitored by a doctor or nurse. The wireless communication is done using RF (Radio Frequency) method. A micro-antenna is used for minimizing the loss of data. The power supply system as seen in Fig. 3 includes wireless power receiving coils and the power regulating circuit. The regulated power is fed through this circuit.

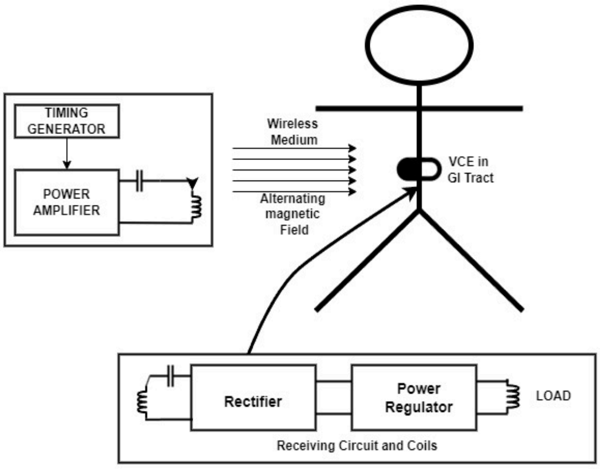


Fig. 3. Overview of the proposed system.

B. Power Transmitting Section Architecture

In this WPT system, we need to create a uniform and strong magnetic field on the transmission side to transfer at least a minimum of 100 mW through the secondary coil which is located inside the VCE itself. To achieve maximum efficiency, we need to have both primary and secondary coils as close as possible to each other and both have to be equal in size and diameter. The secondary coil must be perpendicular to the magnetic field produced by the primary coil. This is the basic theory of wireless power transfer to work and also achieve maximum efficiency [9]. But, in the WCE system, the primary coil is much larger than the secondary coil. Moreover, the RC (Receiving Coil) or secondary coil does not stay perpendicular to the magnetic field as it moves through the body which means the VCE follows an irregular path. Moreover, the distance between two coils is more than 10 cm.

So, to ensure that the power receiver is getting proper power, a uniform, alternating, steady, and strong magnetic field is needed.

C. Power Consumption

The power consumption of the Wireless Capsule can be varied upon its type, application and usage. The maximum power consumption of each part of the capsule endoscope can be found as shown in [11]. The power consumption of primary sections of the capsule consumes roughly 100mW of electrical power. Among this, the CMOS sensor consumes around 25.5 mW, LED consumes 14.8 mW and the MCU consumes 5.1 mW of power. The maximum amount of power consumed by radio frequency communication is 48.9 mW of power. The power consumption can reach much higher than 100 mW depending upon the circuit, components of the circuit, and internal temperature. Transferring power wirelessly by magnetic resonance coupling procedure has created a new portal to the electric vehicle method. It consists of various types of wireless charging capabilities. Although the power transfer rate is comparatively high, its efficiency relies on the displacement of coils. Many types of research are undergoing for ways how to preserve power transfer at high efficiency. But to keep in mind that, in these methods, the coupling coefficient is a must on a system parameter. On the other hand, in charging applications, without communication methods, the information on system parameters won't be available.

Another thing is estimating the system parameters is a quite tough part of applying in the charging system. Here it was given determinations of conditions for assessing coupling coefficients in a few designs of remote force move framework, utilizing data from just one side, either on the transmission side or on the getting side, of the framework. The energy transfer efficiency can be given by Basar *et al.* [12].

$$\eta = \frac{\omega B^2 S\mu_2 R_L Q_1}{(R_2+R_L).^2 L_1} \tag{1}$$

$$\omega = 2\pi f \text{ and } R_2 = \frac{\omega L_2}{Q_2} \tag{2}$$

Here, B is the magnetic field intensity, S is the orthogonal projection area of the secondary coil, μ_2 is the permeability of the coil, ω is the angular frequency concerning the supply frequency f. R_2 is the impedance of receiving coil while the R_L is the impedance of the load. L_1 and L_2 are inductances of the coils and Q_1 and Q_2 are quality factors of the coils.

Taking the constant and variables separately gives us the working equation on which, the design of the coils will be based.

$$\eta = B^2 R_L .X_1 .X_2^2 \tag{3}$$

$$X_1 = \frac{\omega Q_1}{L_1}, X_2 = \frac{S\mu_2}{R_2 + R_L} \tag{4}$$

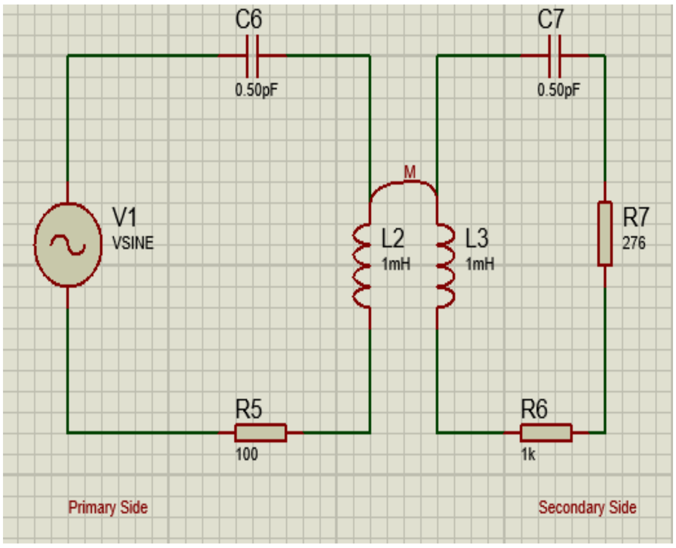


Fig. 4. A SRC WPT model.

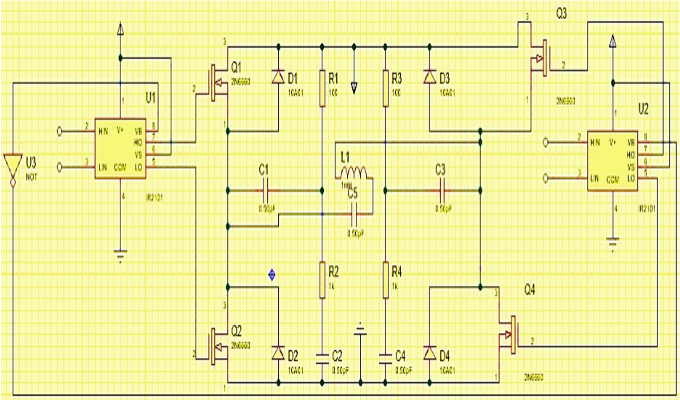


Fig. 5. Transmitting Circuit.

III. DESIGN AND METHODOLOGY

A. *Power Transmitter*

The power transmitting section has 2 main parts, the circuit, and coils. The design and working principle are given in the coming sections.

1) *Amplifying and transmitting circuit*

The transmitting circuit is designed to drive a square wave alternating current as shown in Fig. 5. The coil structure will determine the distribution of the magnetic field created by the alternating current from the circuit. The power supply used can be either an AC supply or a DC supply. Before putting through the TC or Transmitting coils, a Power amplifier is used for achieving a uniform and amplified signal. In the case of a DC supply, an inverter is used to convert the DC power to a square wave AC supply so an alternating magnetic field can be produced. To control the magnetic field easily, 1D transmitting coils are chosen.

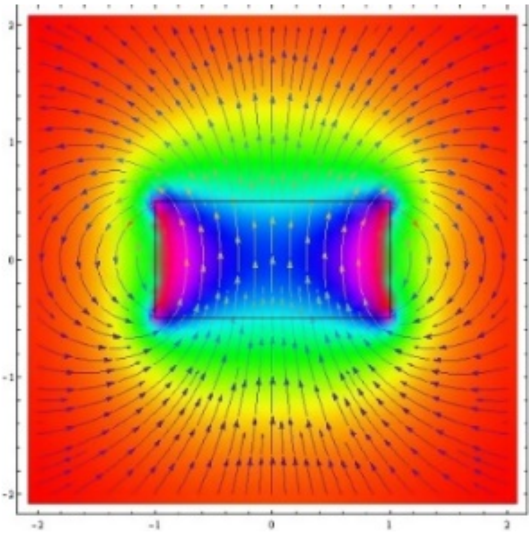


Fig. 6. Magnetic field created by a solenoid.

This circuit includes a class D amplifier for further amplification of the incoming signal from the signal generator. Both class D and class E amplifiers are available in designing of transmitting circuit. Even though the transmitting circuit with a class E amplifier has higher efficiency than a class D amplifier, the class E amplifier's performance is highly sensitive to the parameters of the load network. Due to an unstable load network, a Class D amplifier seems viable in this case. A full bridge class D amplifier can produce twice the voltage of a half-bridge amplifier. So, the full bridge version of the amplifier is adopted. The signal generator produces a square wave signal with a duty cycle of 50%. This signal is fed to the MOSFETS through mosfet drivers. The snubber network is implemented to reduce the overvoltage effect and switching losses of MOSFETs. The class D amplifier is connected to an LC circuit or also known as an LC tank. The resonant capacitor and the transmitting coil are connected in series with a variable inductor. This circuit functions as an electrical resonator, or, to put it another way, an electrical counterpart of a tuning fork, and it assists in oscillating the circuit at the resonant frequency. The main purpose of the variable inductor is to vary the transmitting frequency and always keep it at the circuit's resonant frequency.

2) Transmitting coils

The transmitting coil is the part of the system which will transfer power to the WCE in a wireless medium. This type of coil is also known as an electromagnetic coil. An electromagnetic coil is a helix, spiral, or coil-shaped electrical conductor, such as a copper wire. In applications where electric currents interact with magnetic fields, these electromagnetic coils are used. Such examples are electric motors, generators, transformers, etc. Our system is divided into two parts. Transmitting section and receiving section. Both of the sections require electromagnetic coils to transfer power from one section to another. Electromagnetic coils used in the transmission of power are called transmission coils or TC and the WCE or VCE sections power receiving coil is known as RC or receiving coil. The design and implementation of these coils are faced with a lot of challenges. The optimum design of the power-transmitting coils is discussed below.

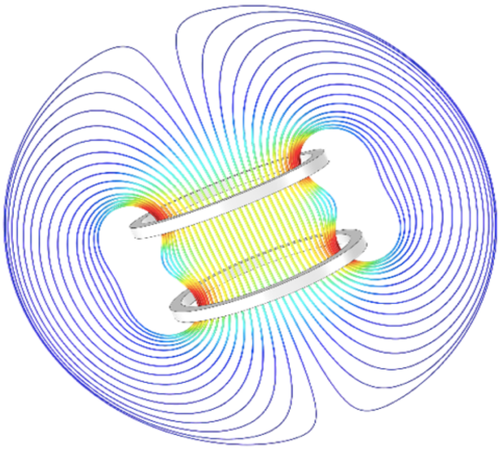


Fig. 7. Helmholtz coil and the magnetic field distribution of the coils.

Even though the intensity of the magnetic field is depended on the magnitude of the signal driven by the transmitting circuit, the uniformity of that field depends on the design structure of the transmitting coil. Uniformity and stability of the produced magnetic field are very important as the RC is located far from the TC and much smaller in terms of the size of the coils. Over that, the orientation of the RC is continuously changing. To achieve maximum efficiency and transfer minimum power to drive the load, the optimum design structure of the TC needs to be obtained. In general, they are two types of TC which are solenoid coils and Helmholtz coils [6].

Both Helmholtz structure and much simpler solenoid structure have their advantages and disadvantages. From previous research, we can see that, due to its simple structure, a solenoid coil is easy to design and implement, but its main drawback is the non-uniformity of the induced magnetic field which in return may create unstable power at the receiver [12]. A comparative study by Basar *et al.* [13] suggests that the field uniformity is the best in Helmholtz coils. In this paper we experimented with Helmholtz coil configuration to create a uniformly distributed magnetic field.

The coils implemented by the authors are shown in Fig. 8 and Fig. 9. The transmitting coils are constructed with Litz wire (enameled copper wire). The wire is winded for 30 turns for each solenoid. Wire parameters are 180 strands of AWG 38. The total Diameter of each coil is 300 mm, the height is 250 mm and the distance between the two coil pairs is 180 mm. The TC has a 250 pF capacitance in series. The total inductance is measured by the LCR-8000G Series LCR meter to be 582 μH. The AC supply through the transmitting circuit is supplied by an AC signal generator.

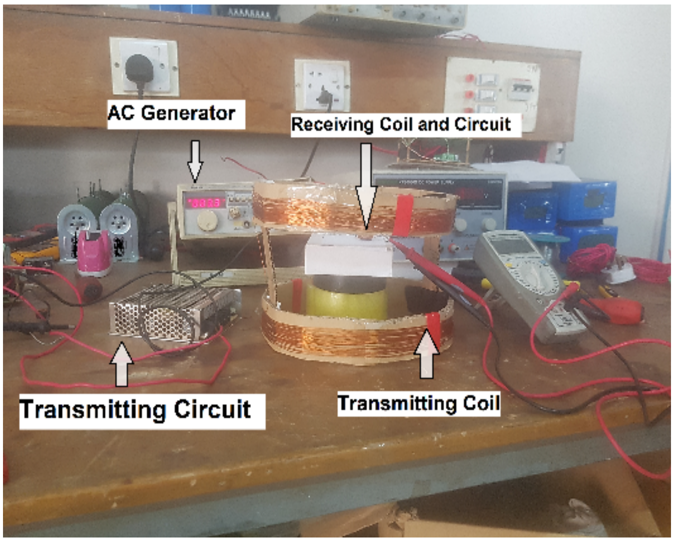


Fig. 8. Implementation of Helmholtz coils and experimental setup.

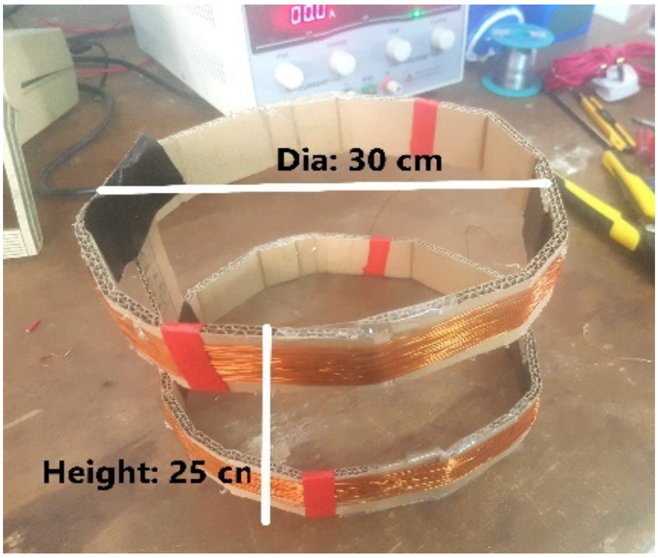


Fig. 9. Implementation of Helmholtz coils.

3) Power transmission frequency

As seen in (2), the efficiency depends upon X1 which depends on the angular frequency, the inductance of the coils, and the quality factor. We use the GWInsTek LCR-8000G Series LCR meter to obtain the Q and L values and determine X1 at a frequency range of 150 kHz to 500 kHz.

B. Power Receiver

The power receiving section of the system is the VCE itself which includes, receiving coils, a CMOS imaging sensor, LED lighting, and an RF transmitter. It also needs a 3D full bridge rectifier circuit followed by a voltage regulator circuit.

1) Power receiving circuit

Here, marked as L1, L2 and L3 are 3 independent receiving coils wounded into a single ferrite core. Each coil is connected to a full bridge rectifier circuit for conversion from AC to DC. Cf capacitor is used to remove the ripples from the DC power. The voltage regulator is connected in parallel to maintain uniform power supplied to the VCE.

The design and structure of the 3D receiving coil are discussed in the next section.

2) Power receiving coil design and structure

Some of the main challenges faced while designing the system is the difference between TC and RC. Both of them are different in size and also the orientation of the RC always changes while the capsule is being passed through the gastrointestinal tract. As a result, the power received is not always equal or efficient enough to drive the load circuit. The minimum power that needs to be transmitted, as mentioned before is at least 100mW.

In this paper, we follow the design of a 3D transmitting coil [6]. Basically, in this design, we have tried to overcome the orientation problem as much as possible. Multiple receiving coils oriented in 3 different directions have been designed and implemented. Each of coils 1, 2, and 3 are orthogonal to each other and all of them are wounded on a common ferrite core. In theory, structuring 3 different coils in 3 different directions will eliminate or reduce the power deficiency problem of the circuit as the device moves through the human tract.

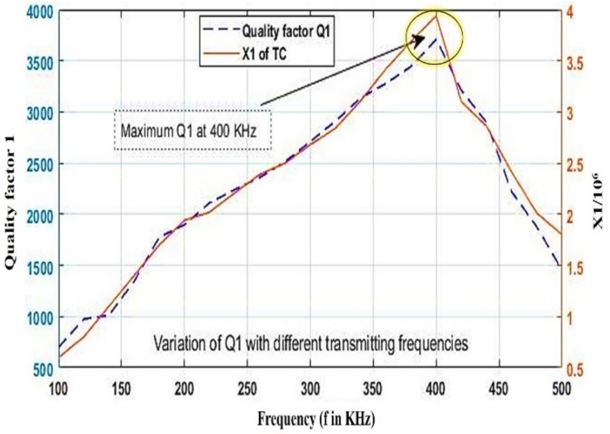


Fig. 10. Variation in quality factor at different frequencies.

Some parameter that is kept in mind while designing this system is that the wire used here is Litz wire to reduce skin and proximity effect losses in coils. The quality factor of the wire is also taken into consideration.

But out of all, the most important design parameter is the number of turns in each coil. As the space is restricted, one of 2 viable options is available to us. One of them is higher number of turns with lower number of strands and the other option is to use lower turns with higher number of strands. We select the structure of coil which has the highest Q value. To simplify the matching of impedance, the RC impedance is set to equal the load impedance which is achieved at a frequency of 400 kHz.

From (3), we can determine the quality factor of the receiving coils and find out the optimum coil type and strand in order to achieve maximum efficiency [14].

$$X_2 = \frac{S\mu_2}{R_2 + R_L} \tag{5}$$

The inductance of the secondary coil L2 is proportional to the number of turns in the coil n.

$(L_2 \propto n)$ and inversely proportional to the number of strands N, the secondary coil's impedance R_2 is also proportional to n and inversely proportional to N.

$$(L_2 \propto \frac{1}{N}) \tag{6}$$

To determine the coil, turn and the number of strands to be used in a coil to achieve maximum efficiency, we connect the 3D coil to a resistive load to simulate the VCE and analyze the received power and quality factor Q by changing the number of strands.

The number of turns of each coil and the strands to be used is determined by obtaining receiving power P2 when the transmitting circuit is supplied by AC of 1 A at 400 kHz. The quality factor Q_2 of the coils is also measured using an LCR meter at different transmitting frequencies. A single strand of Litz wire is 44 AWG [12].

The quality factor and power variation of the coils in the case of 2 strands with 150 turns and 1 strand of 250 turns for 1 coil while other coils are opened; can be seen in Fig. 14.

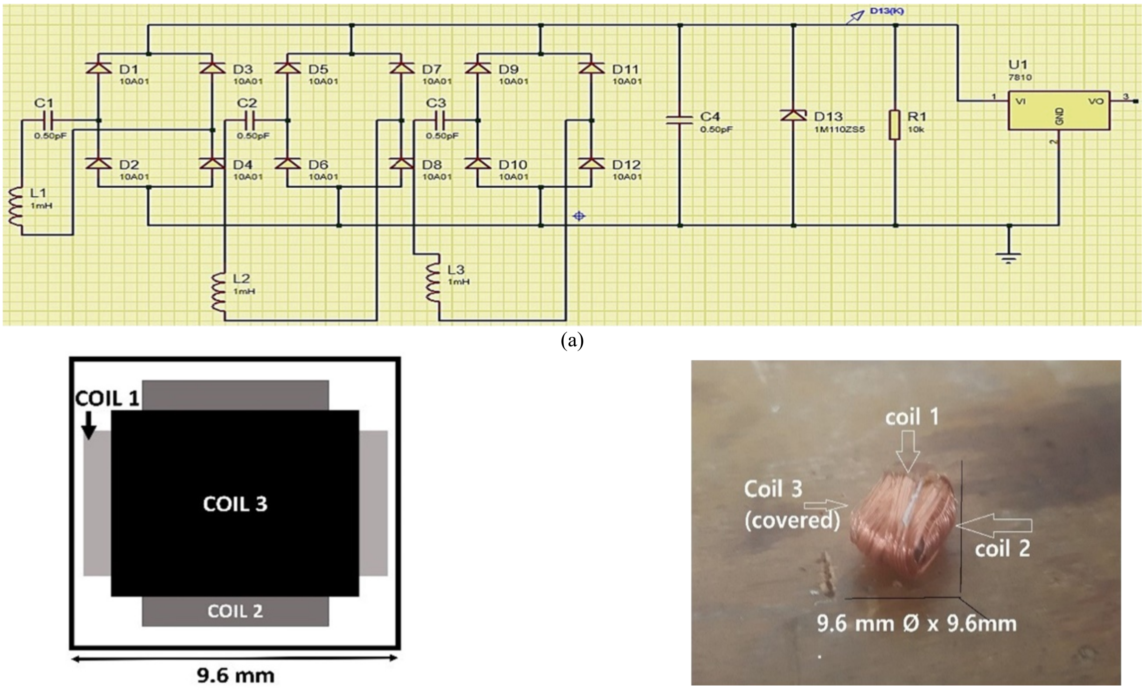
As seen in Fig. 11a, a lower turn with a higher strand number gives us better performance. Due to space constrictions, we choose 2 strands with 150 turns for receiving coil as seen in Fig. 10d. The dimensions for 3D coils are given in Table I.

C. Statistical Analysis and Graphical Representation

The various data throughout the experiment were measured using Multimeters and inductance, and impedance is measured using a GWInsTek LCR-8000G Series LCR meter. For graphical representation, we used MathWorks MATLAB R2021b. Vizag and COMSOL Multiphysics simulation software is used for the simulation of magnetic fields of various models of coils. Proteus and LTspice XVII were used for electrical circuit simulations. The graphical data generated from the statistical data obtained were further verified using GraphPad Prism (Ver. 8.0.1) [15]-[18], and R programming script (R-4.0.2) [19]-[22]. Tukey's multiple comparison test among the quality factors (Q) was carried out [23]-[27] to recapitulate the static deflections with different rational angles and frequency as part of verifying the newest results obtained.

TABLE I: DIMENSION OF THE COILS

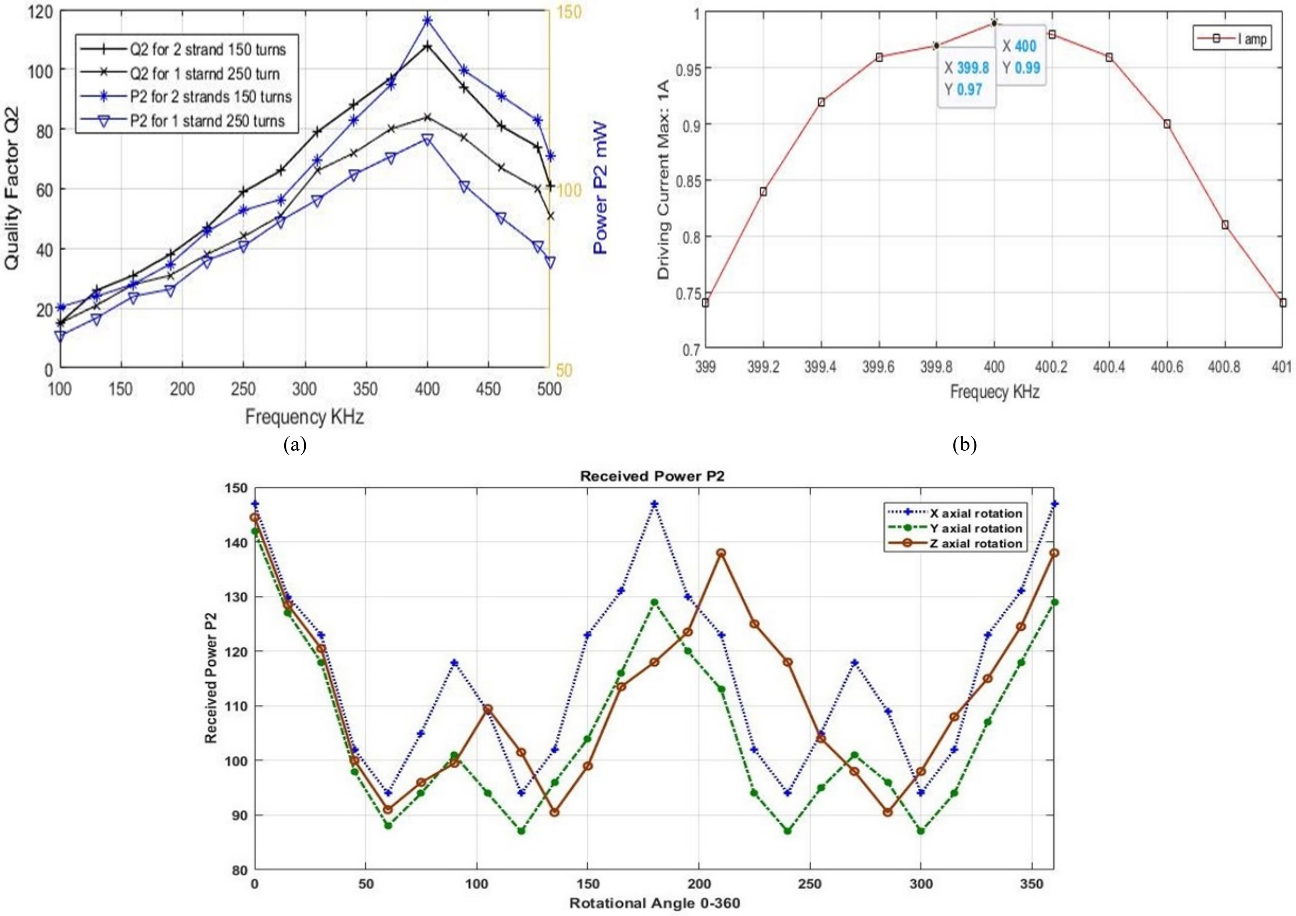
Coil	Turn No.	Dia. × Length mm	Wire Gauge	Strands	Q2 Value	P2 value mW	Frequency
1	150	Ø 9.6 × 9.6	44	2	108.7	147.58	400
2	140	Ø 9.6 × 9.6	44	2	107.24	146.2	400
3	130	Ø 9.6 × 9.6	44	2	107.8	107.8	400



(a)

(b) (c)

Fig. 11. a) Schematic of power receiver circuit; b) 3D structure of coils for receiving subsection; c) 3D receiving coil.



(a) (b)

(c)

Fig. 12. a) Changes in Q2 and P2 for two configurations of Receiving Coils; b) Driving current with varying supply frequency; c) Result of orientation experiment: Power received by VCE.

IV. RESULTS

To obtain the performance of the whole system, the stability of supply current, frequency, and power received by the secondary circuit at various rotational points of receiving circuit or the VCE is measured.

A. Stability of Supply Frequency

Due to the movement of the body and changes in the shape of the transmitting coils, the inductance of the coil's changes too. The changes in driving current due to the non-uniformity of the coils can be seen in Fig. 11b. The driving current remains almost close to 1 A for frequency variation up to +-0.5 KHz.

B. Receiving Power

The receiving power on the VCE is examined while the transmission frequency is 400 KHz and the current is 1A. The VCE is rotated and propagated through the air medium independently in 3 dimensions orientation to achieve both the best and worst possible position. The received power and efficiency of the system are demonstrated in Fig. 12.

Fig. 12c depicts the variation of transferred power to the wireless capsule in 3 different dimensions. The receiving capsule or the receiving coils seen in Fig. 11b and 11c is placed inside the power-transferring coils seen in Fig. 9. The coil configuration in the receiving section is divided into 3 dimensions so that the capsule receives the maximum power irrespective of its position and orientation. To obtain the maximum and minimum power received by the capsule, the position and the orientation of the receiving coil are varied at a specific interval. Each coil (X, Y, Z axis) of the receiving coils has a specific angular position respective to the magnetic field produced by the power transmitting coils. In this research, the power received at each coil was measured independently of other coils while varying its angular orientation. It is seen from Fig. 12c that the power received by the coils receives its peak value at 0º, 180º and 360°. The maximum power, 147 mW is received when the X axial coil is perpendicular to the transmitting magnetic field. The least amount of power 88 mW is received when none of the 3 axial coils is perpendicular to the magnetic field.

V. CONCLUSION AND DISCUSSION

Video Capsule Endoscopy (VCE) is a medical device that is used in an endoscopy procedure. The main objective of the device is to take pictures at a specific rate and transmit the pictures through the Radio transmitter inside the VCE. It is a rather easy endoscopy procedure. But there are challenges to this. One of the main challenges is the operation time of the VCE and the quality of the picture and frame rate. All of these issues are directly connected to the available power in VCE. A general endoscopy may last as long as the digestion period of a human being. On average the digestion period of an adult is about 12+ hours. But the traditional VCE which is powered by batteries can only operate for only 7-8 hours. Moreover, the better the picture quality is the higher the power consumption. Generally, the diagnosis ends prematurely due to a lack of power on board. In this paper, we have given a solution to this problem which is to provide the VCE with external power. The power will be transmitted to the VCE through the wireless medium by the means of electromagnetic coupling. Electromagnetic coupling requires two coils known as transmitting and receiving coils and alternating current through the transmitting coils creates an alternating magnetic field. The secondary coil receives alternating current from this magnetic field. But, in this case of VCE, we had to face and overcome some challenges such as the various size and varying distances between the TC and RC. The solution to these problems has been discussed in this paper which is to drive the transmitting coil with the resonant frequency. In this research, to transfer maximum power through the wireless medium, a Helmholtz coil configuration was used. Research conducted by [28] also shows that even though multiple different techniques for wireless power transfer coil configuration exists, the Helmholtz coil is the most usual choice as its inner diameter is greater than the transverse dimension of the human body. Also, this coil is easy to implement. Due to its not uniformity of magnetic field, the received power is maximum near the coil and minimum at the center of the field. These phenomena can be observed in Fig. 11c. In terms of coil turns, coil windings, diameter, and wire type, this research uses Litz-enameled copper wire which is winded for 30 turns in each solenoid. The wire parameters are 180 Strands of AWG 38. The diameter of each solenoid is 300mm while the height is 250 mm. The transmitting frequency is 400 KHz. A similar coil configuration is observed in research done by [14],[28], and [29]. Also, a class D power amplifier has been used before TC coils to increase the transmitting power level so that the magnetic field created is strong and uniform.

The second area is the size of the receiving coils. The receiving coils are very small in size and also move with the VCE itself. To ensure that the RC receives maximum power, a 3-dimensional structure of the RC has been proposed so that no matter the orientation of the receiving coils, at least one of the 3 coils is perpendicular to the magnetic field and is receiving the maximum power. A 2D and 3D design for the power receiving circuit can be seen in [30]. In our experiment, we were able to transfer a maximum power of 147 mW through a wireless medium which is enough to power up a VCE with the most basic components was able to transmit power up to 160 mW while the transmitting frequency of this research varied from 100 KHz to 700 KHz. Almost 170 mW of wireless power transfer to the VCE at worst geometrical conditions was achieved by the [31], [32]. The research by [12] was able to transmit a much higher wireless power, which is 376 mW at a lower transmitting frequency. The minimum power received at the worst geometrical condition of the positioning of this research is 88 mW. The efficiency remains between 1-2% depending upon the angular position of VCE to the magnetic field of transmitting coils. One of the primary reasons for low transmission efficiency is the build quality of the receiving coils as well as the receiving circuit which converts the alternating current to usable DC. We have also experimented with a change in transmitting current as it is correlated with transmitting frequency which might change due to movement in transmitting coils.

The feasibility of using a wireless power system instead of batteries is studied in this paper. We can see that even though we can transmit the power needed for VCE for most of the experiment, the received power is less than 100mW at the worst angular positions of VCE. Our future work will focus on improving the transmitting efficiency of the system and improving the minimum received power in VCE. Further research will be done by testing the prototypes on animals.

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