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# DbSWPT: A Novel Distance-based Switch for Efficient Wireless Power Transfer in Battery-less Wireless Capsule Endoscopy

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**Abstract-** Capsule endoscopy (CE) is a revolutionary technology for a comprehensive exploration of the small intestine. It is widely recommended worldwide due to its ease of use, and lower pain levels compared to traditional endoscopy. Nevertheless, the restricted power supply of batteries hampered the progress of the capsule endoscopy industry. In this paper a novel distance-based switch, called DbSWPT was proposed for efficient wireless power transfer (WPT) system. It targets battery-less wireless capsule endoscopy (WCE). The proposed system consists of two separate coils with distance significant impact. To tackle problem, a distance-based switch configuration is proposed between two variable load resistances according to distance between transmitting and receiving circuits. Results proved high efficiency at short distances using potentiometer in decreasing direction which starts with high resistance values and then decreases to a certain value of resistance according to measured distance whereas the other has a high efficiency at long distances using potentiometer in increasing direction which starts with low resistance values and then increases to certain value of resistance according to measured distance. The results illustrated that the system performance using series-series (S-S) configuration is superior to using the parallel-parallel (P-P) configuration. It is found that the minimum efficiency for the proposed P-P distance-based switch is 51%, while for the proposed P-S is 83.33%. Accordingly, the proposed switch-based S-S configuration achieved minimum efficiency 90.91%. It increases the efficiency by 8.34%.

**Keywords-** Capsule endoscopy, wireless power transfer, distance-based switch, efficiency, battery-less, potentiometer.

## I. INTRODUCTION

Gastrointestinal (GI) tract disorders are considered common diseases due to the widespread of malignant diseases, such as gastric cancer, tumors, and bleeding [1] [2]. Early detection of such diseases is critical for successful prevention and to avoid complications. This leads to the urgent need for the evolution in the CE technology to stride toward clinical use. The CE allows the physician to examine the small intestine by collecting and transmitting high-fidelity images along the capsule's path in real-time, making painless/easier diagnosis [3]. It can reach areas in the GI tract, where the traditional endoscopes cannot reach, including the small bowel [4] [5] [6]. The CE is also recommended for patients who have narrowing in the digestive tract, Crohn's disease, or past surgery in the GI tract. The "Given Imaging" company reported an endoscopy consists of the CE, data delivery module, a work station, and software package as main parts of the WCE system [5] [7]. The captured images of the GI tract by the moving WCE through the GI tract are wirelessly broadcasted exterior the patient's body and received by a delivery module attached to the patient's waist. The capsule

includes a camera, light source, processing/control units, and a transmitter for wirelessly transmitting the acquired images/videos to an external reception system. These components and processes in the WCE system require at least eight hours inside the body [5] [8].

The WCE is powered by a battery that may run for up to 6-8 hours on a single charge [9]. This leads to limitations on the WCE including the inspection of a small intestine portion due to the battery lifetime, which necessitates the use of the WPT systems to cut out the battery [10]. Therefore, the required working duration of the WCE is a key bottleneck in the battery based WCE design, which in turn, limits the duration of the clinical examination using the WCE. These limitations attract researchers to attempts for reducing the power consumption of the various components of the WCE system [11]. The external rechargeable batteries (from an extra-corporeal power supply) are manufactured using radio frequency (RF), microwave, or electric induction technologies, as well as "battery-free" WCE employing WPT technology [9]. A trade-off between the number of batteries according to the required power and the overall size of the capsule should also be considered. This initiates the development of WPT technology to charge the battery inside the capsule during the WCE journey within the GT. Using standard WPT, a transmitting coil (TC) is wrapped around the patient's body that increases the electromagnetic field when high frequency alternating current flows through it. A receiving coil (RC) is integrated with the capsule in a wirelessly controlled CE device. Due to the formed magnetic field by the TC, the RC cannot entirely receive the total power generated and a portion of the energy is lost during the transmission. Thus, the current in the RC becomes slightly smaller than that in the TC [12]. The magnetic resonant coupling can be improved by using resonant frequencies to enhance the efficiency of the system [9]. The size of the RCs must be limited to make the WCE device work efficiently [9]. Hence, different WPT topologies can be evaluated with the CE system to reach out the best configuration.

There are various configurations for WPT system, including P-P, P-S, series-parallel (S-P), and S-S configurations [13] [14]. Fang *et al.* [4] implemented a WPT device for WCE based on the strongly coupled magnetic resonance principle using S-S configuration of four coils, an excitation source, and a load. The results showed a maximum system efficiency of 26.14% at a working frequency of 8.2 MHz. Moreover, Guo *et al.* [5] developed a sinusoidal generator transmitter/receiver equivalent circuit leading to 95% transmission efficiency using S-S WPT system at a frequency of 3.7 MHz. For an active capsule endoscope, Miah *et al.* [9]

designed a 1050 kHz WPT system using S-S configuration with the capsule RC placed in a hollow body phantom as well as one filled with colon-equivalent liquid to test the output of the WPT device. The performance of the power transmission was investigated in relation to the operating frequency and the load resistance, showing that a hollow and a liquid phantom can achieve maximum power transfer efficiency 20.4%, and 17.47%, respectively.

The various conducted studies show that high efficiency can be acquired at low distances, while low efficiency occurs at high distances between the transmitter and the receiver. To overcome this challenging issue, this paper proposed a switching based WPT (DbSWPT) system with two concepts: i) to toggle between the two circuits, and ii) to toggle between two potentiometers, where our results showed the superiority of the second proposed concept. This paper enhances the efficiency of various traditional configurations especially at high distances. Although the digestive system contains many convolutions, the distance between the bagger and capsule can be measured by considering convolutions as a 2D plane.

## II. METHODOLOGY

The challenge issue in the fabrication of the WCE is its short life battery and the trade-off to design small WCE [1] [15]. The WPT system is used to solve this challenge by charging the battery after the patient swallows the capsule or cutting out the battery. However, the last solution requires the very high efficiency of the used WPT along all distances between the bagger and capsule circuits.

The existing WCE systems use traditional configurations that based on two separate circuits, which consist of sinusoidal generator, resistances, capacitors, transmitted and receiving coils. Various configurations come from different arrangement of elements. This paper proposed a switching module between two variable load resistances according to distance between the transmitting and receiving circuits by using 8.2 MHz frequency with assuming maximum distance between the bagger and capsule circuits 0.5m distances. The used frequency in the range of basic safety limitation of human body tissue by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and Japan Society of Medical Electronics and Biological Engineering (JSMEBE) [16] [17].

### A. Traditional Configurations

Since there are various circuit configurations for the WPT system, this section focuses on the S-S configuration as it achieves the highest system efficiency than others [18] as will be explained later.

#### a. Series-Series (S-S) Configuration

The S-S configuration consists of two resonant circuits as shown in Fig. 1. The first circuit is the bagger circuit that consists of a sinusoidal generator, series capacitor, and transmitting coil that in series with a resistance. The second is the capsule circuit which consists of the receiving coil that is magnetically linked with the transmitted coil and in series with the resistance and capacitance.

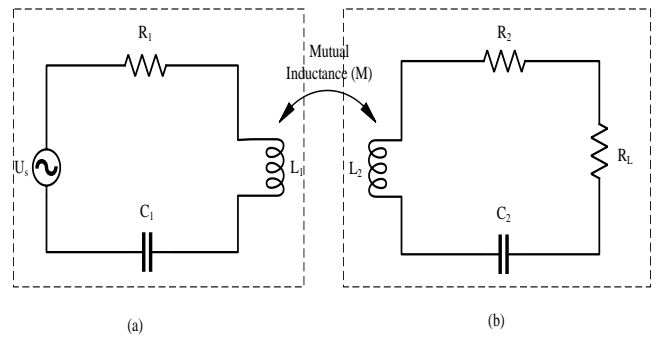


Figure 1: Traditional S-S configuration, where: (a) bagger circuit, (b) capsule circuit.

The current generated in the bagger circuit by the sinusoidal generator is the same current that reaches the transmitting coil and generates the maximum magnetic field. Therefore, the transferred power to the receiving circuit will be maximum [19] [20], where the power efficiency between bagger and capsule circuits can be formulated in few steps as shown next equations respectively by applying KVL in circuit shows in Fig. 1 as follows [21]:

$$U_s = Z_1 I_s - j\omega M I_L \quad (1)$$

$$0 = Z_2 I_L - j\omega M I_s \quad (2)$$

where  $U_s$  is the voltage source,  $M = K\sqrt{L_1 L_2}$  is the mutual inductance between the bagger and capsule coils, and  $K$  is the overall coupling coefficient. The mutual inductance between the coils can be represented as follows [15]:

$$M = \frac{4\pi^2 10^{-7} n_1 n_2 a^2 b^2}{\sqrt{(a+b)^2 + d^2} \sqrt{(a-b)^2 + d^2}} \quad (3)$$

where  $n_1$  and  $n_2$  are the number of turns,  $a$  and  $b$  are the coil radius of bagger and capsule, respectively. Also,  $d$  is the distance between the bagger and capsule circuits.  $Z_1$  and  $Z_2$  are the total impedance at the bagger and capsule circuits, which can be expressed as follows [21]:

$$Z_1 = R_s + \frac{1}{j\omega C_1} + R_1 + j\omega L_1 \quad (4)$$

$$Z_2 = j\omega L_2 + R_2 + \frac{1}{j\omega C_2} + R_L \quad (5)$$

where  $R_s$  is the internal resistance of power source,  $U_s$ ,  $C_1$  is the series capacitance of bagger circuit,  $L_1$  is the primary coil inductance, and  $I_s$  is the current of bagger circuit. By solving Eqs. (1), and (2), the current through bagger and capsule coils can be given, respectively, by [21]:

$$I_s = \frac{U_s Z_2}{Z_1 Z_2 + (\omega M)^2} \quad (6)$$

$$I_L = \frac{j\omega M U_s}{Z_1 Z_2 + (\omega M)^2} \quad (7)$$

The coupling efficiency,  $\eta$  can be simply expressed as:

$$\eta_{ss} = \frac{\text{output power across } R_L}{\text{output power across } R_L + \text{Total power losses}} \quad (8)$$

Thus, the system efficiency of S-S configuration can be given by:

$$\eta_{ss} = \frac{\omega^2 M^2 R_L}{(R_2 + R_L)[R_1(R_2 + R_L) + \omega^2 M^2]} \quad (9)$$

Thus, the system efficiency is inversely proportional to the series resistance  $R_2$  in the capsule circuit, and directly proportional to the load resistance  $R_L$ . The overall efficiency can be increased at both short and long distances by controlling the load resistance. In all WPT configurations, the system efficiency is directly proportional to the mutual inductance  $M$ , and the coupling coefficient  $K$ . Consequently, when the bagger circuit is near/ close to the capsule circuit, or when the distance between bagger and capsule circuits is short, the mutual inductance becomes high. On the other hand, when the bagger circuit is far from the capsule circuit, the mutual inductance becomes low and decreases with increasing the distance which results in decreased system efficiency [22] [23].

**B. The Proposed Distance-based Switch Configurations**

In the above traditional S-S configurations, only two circuits (Bagger and Capsule) are involved in measuring system efficiency along with all values of distance leading to very small efficiency for long distances. Consequently, in this paper, we overcame the low efficiency at long distances by using the proposed switching concept as shown in Fig. 2.

To implement the distance-based switch, one bagger circuit, and two capsule circuits at the receiver (Capsule) are proposed as shown in Fig. 2. One of the two circuits at the receiver is used to realize high efficiency at low distances, while the other circuit is used to realize high efficiency at high distances. However, in this configuration, it leads to high complexity in the capsule circuit in terms of large size and cost.

To tackle this problem, another configuration based on the distance-based switch as illustrated in Figs. 3 through 5 using S-S, P-P, and P-S configurations, respectively. These configurations include the use of one bagger circuit, one capsule circuit, and a switch between the two potentiometers as load resistances. The two potentiometers are proposed to guarantee high efficiencies regardless to the distance, where a potentiometer for short distances, and the other is for long distances. The switch will be toggled dependent on measuring

the distance between the transmitting and receiving coils by using a distance sensor. In this paper, we focus on improving the system efficiency by simulating the two cases of short and long distances to determine the load resistance value, which is the main influencing factor. Then, a switch is proposed to change the used circuit based on the detected distance according to the capsule location in the GT track, where an intersection point between using each circuit to achieve for high efficiency was determined.

**a. Series-Series (S-S) Distance-based Switch Configuration**

This configuration is similar to the traditional S-S configuration with adding a switch between the two variable load resistances to enhance the system efficiency at short and long distances as shown in Fig. 3.

The system efficiency can be formulated as follows:

$$\eta_{ss} = \frac{\omega^2 M^2 R_L}{(R_2 + R_L)[R_1(R_2 + R_L) + \omega^2 M^2]} \quad (10)$$

where  $R_L$  is the variable load, which is given by:

$$R_L = \begin{cases} R_{L-low} & \text{at } d < 0.25m \\ R_{L-high} & \text{at } d > 0.25m \end{cases} \quad (11)$$

where  $R_{L-low}$  is the load resistance for short distances, which has values less than 0.25 m and  $R_{L-high}$  is the load resistance for long distances, which has longer distances than 0.25 m.

**Parallel-Parallel (P-P) Distance-based Switch Configuration**

In the parallel-parallel (P-P) configuration, the efficiency is lower than in the S-S, where the transmitting coil  $L_1$  is parallel to the capacitance  $C_1$  and the amount of current flows through the transmitting coil is smaller than the current generated by the signal generator. Consequently, the electric field through  $L_1$  is small and the amount of power that will be transferred is lower. Besides, the capsule circuit uses the concept of switching to choose the appropriate load resistance according to distance measured by distance-sensor between the two circuits as shown in Fig. 4.

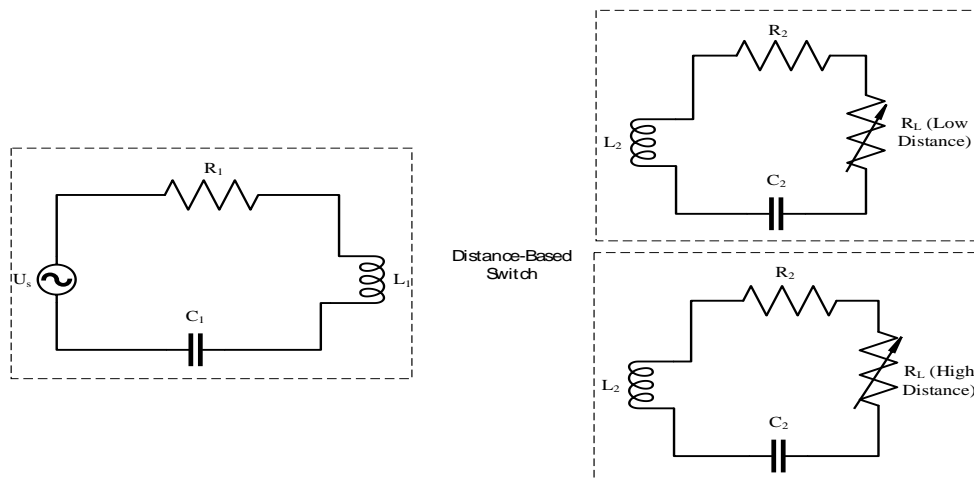


Figure 2: The S-S distance-based switch configuration using one bagger circuit, two capsule circuits.

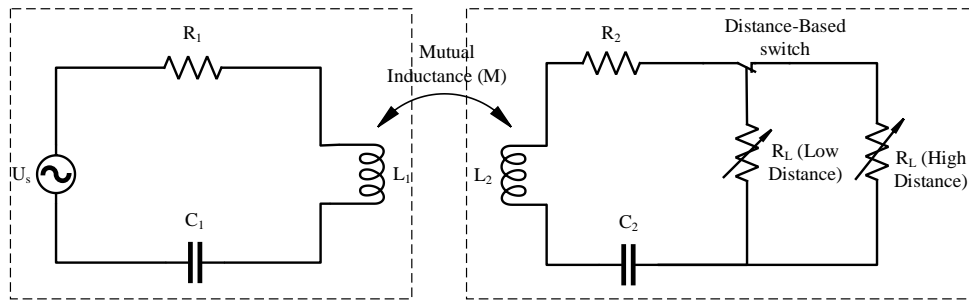


Figure 3: The S-S Distance-Based Switch configuration using one bagger circuit, one capsule circuit

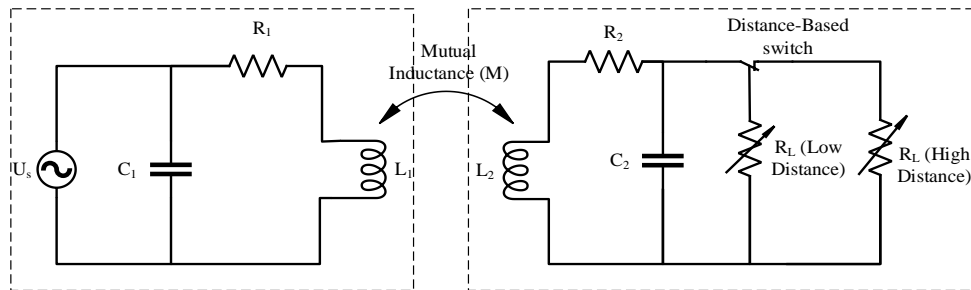


Figure 4: The P-P distance-based switch, where: (a) bagger circuit (transmitter), and (b) capsule circuit (receiver).

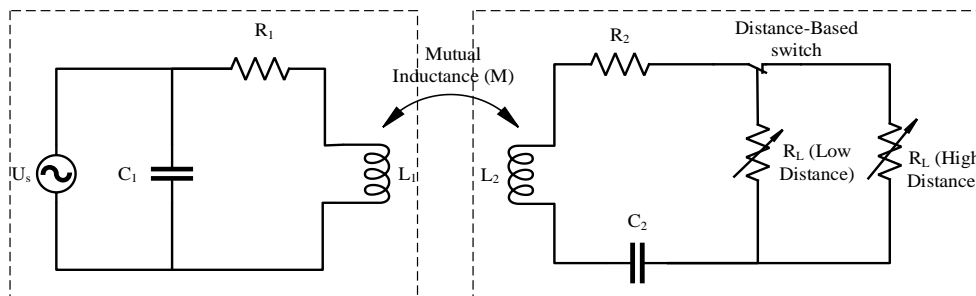


Figure 5: The P-S distance-based switch configuration.

### c. Parallel-Series (P-S) Distance-based Switch Configuration

The P-S configurations is shown in Fig. 5, which shows the arrangement of R,L,C in both bagger and capsule circuits. As in P-S configuration, the transmitting coil  $L_1$  is linked in parallel to the capacitance  $C_1$ , and the amount of current that flows through the transmitting coil is smaller than the current generated by the signal generator. However, the induced current generated through the receiving coil is the same as current flows through the load resistance and then the power received will be increased compared to the power received in P-P distance-based configuration.

To find the efficiency for the bagger and capsule circuits, the following formulas are applied:

$$U_s = \frac{1}{j\omega C_1} I_{C1} \quad (12)$$

$$U_s = (R_1 + j\omega L_1) I_{L1} \quad (13)$$

$$0 = Z_2 I_{L2} - j\omega M I_{L1} \quad (14)$$

where  $Z_2$  is the total impedance at the capsule circuit, which can be given by:

$$Z_2 = j\omega L_2 + R_2 + \frac{1}{j\omega C_2} + R_L \quad (15)$$

By solving Eqs. (11)-(13), the system efficiency of P-S configuration ( $\eta_{ps}$ ) can be expressed as follows:

$$\eta_{ps} = \frac{\omega^2 M^2 R_L}{\left\{ \left[ (R_1 + j\omega L_1) // \frac{1}{j\omega C_1} \right] (R_2 + R_L) + \omega^2 M^2 \right\} (R_2 + R_L)} \quad (16)$$

where  $R_L$  is the variable load, which is given by:

$$R_L = \begin{cases} R_{L-low} & \text{at } d < 0.25 \text{ m} \\ R_{L-high} & \text{at } d > 0.25 \text{ m} \end{cases} \quad (17)$$

where  $R_{L-low}$  is the load resistance for low distance which less than 0.25 m,  $R_{L-high}$  is the load resistance for high distance which higher than 0.25 m.

### C. Proposed Switch-based WPT System

There are two options of DbSWPT. First consists of only one bagger circuit and two capsule circuits (one for distances less than threshold distance and one for distances more than threshold distance). In this case the switch will be before two circuits and according to distance, the switch will choose the suitable circuit. Second consist of only one bagger circuit and only one capsule circuit in addition to using two potentiometers (one for distances less than threshold distance and one for distances more than threshold distance). In this case the switch will be before two potentiometers to choose

the suitable one. The second option is more appropriate since using only one capsule circuit will reduce capsule endoscopy sizing and making it easier to swallow.

This paper chooses the S-S distance-based switch configuration as a WPT system for CE due to its simplicity and its higher efficiency at both short and long distances and has higher intersection efficiency at intersection point as will be shown in next section. The overall block diagram of the proposed system is demonstrated in Fig. 6.

### III. RESULTS

The simulation results of the proposed wireless power transfer configurations were implemented using MATLAB 2017a. The relationship between the efficiency and distance for the S-S configuration was depicted, then, the results of the distance-based switch of the other configurations were discussed.

#### A. Distance-based Switch in the S-S configuration

In the S-S configurations, the circuit parameters will be as shown in Table 1. Fig. 7 demonstrates the system efficiency versus the transmission distance  $d$  in meter as given in Eq. (10).

Each subplot of Fig. 7 consists of two y-axes. Red y-axis of Fig. 7(a) demonstrates decreasing potentiometer of load resistance with increasing distance between bagger and capsule coils and blue y-axis reflects the effect of this on the efficiency from Eq. (10). Red y-axis of Fig. 7(b) establishes the increase of the potentiometer of load resistance with increasing the same distance and blue y-axis reflects the effect of this on the efficiency from Eq. (10).

Figure 7 illustrated that the efficiency is inversely proportional to the increase in distance between the two circuits when the load resistance is decreasing as shown in Fig. 7(a), while it is proportional to  $d$  when the load resistance is increasing as shown in Fig. 7(b).

In Fig. 7(a), the maximum efficiency that obtained at zero distance is 90.91%, which is acceptable, while the minimum

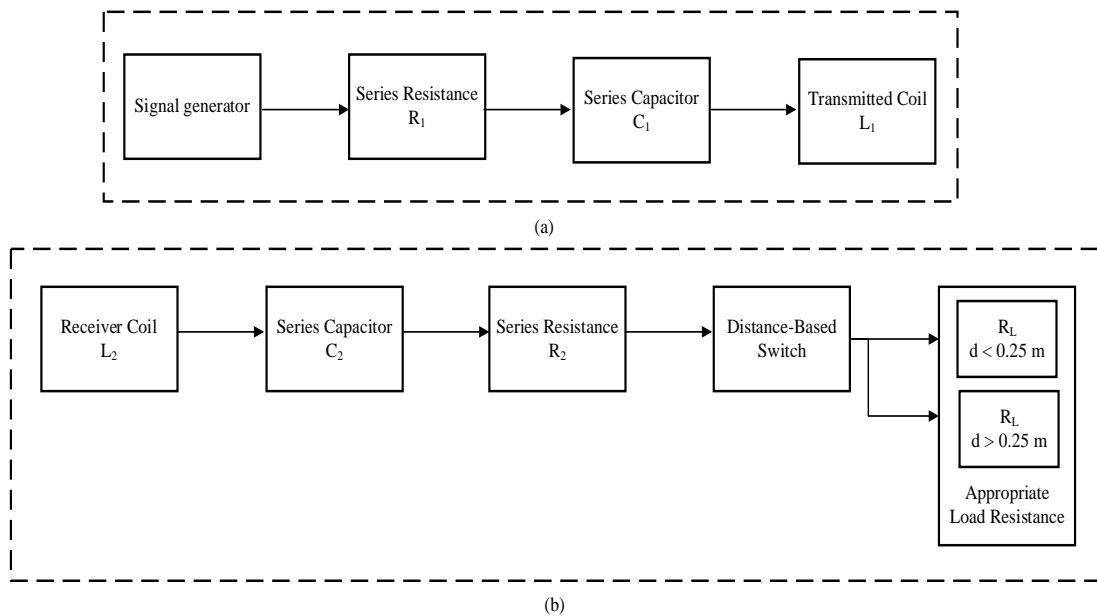
efficiency at a maximum distance (0.5 m) is 0%, which is unacceptable value in wireless power transfer systems. On contrary in Fig. 7(b), the obtained maximum efficiency at long distance is 90.91%.

IN OUR PROPOSED CONFIGURATION, BY COMBINING BOTH CURVES FOR SHORT AND LONG DISTANCES, THE PERFORMANCE OF THE S-S TRADITIONAL CONFIGURATION OF THE WPT SYSTEM IS IMPROVED AS ILLUSTRATED IN FIG. 8. The switching circuit is used to obtain acceptable efficiency through the whole distances of the capsule through the GT track in the modified system. It is noticed that, since as assumed the maximum distance between bagger circuit and capsule circuit is 0.5 m, the values of the load resistance have an important effect on the efficiency for this distance. Fig. 8 plots two relations.

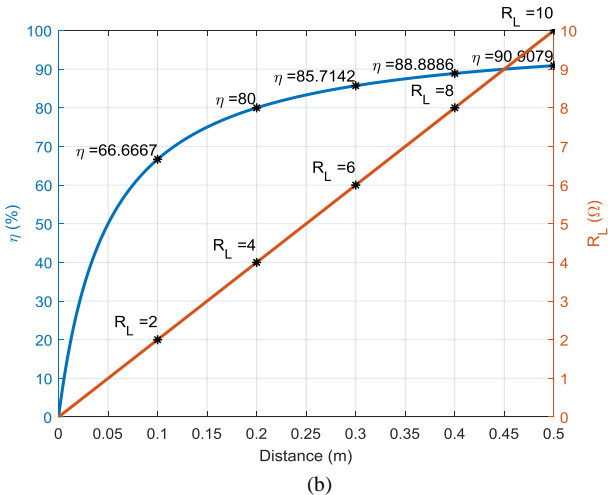
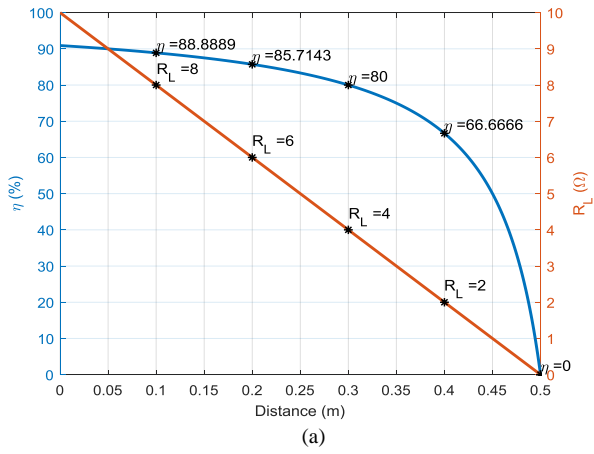
First, between load resistance value ranges on red y-axis and distance and shows the switching point at the middle of distance between two circuits. Second, between efficiency on blue y-axis and distance and shows the same switching point at first. And the two intersected curves will be demonstrated in Fig. 9.

**Table 1: The Parameters of WPT capsule endoscopy at  $f=8.2$  MHz**

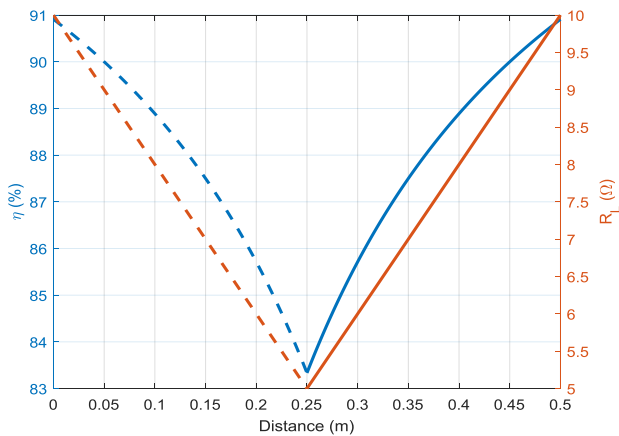
| Parameters  | Parameters Values        |
|---|--------------------------|
| Radius of bagger coil ( $a$ )                           | 0.1 m                    |
| Radius of capsule coil ( $b$ )                          | 0.092 m                  |
| Number of turns for bagger coil ( $n_1$ )               | 10 turns                 |
| Number of turns for capsule coil ( $n_2$ )              | 10 turns                 |
| Range of load resistance ( $R_L$ )                      | 0 $\Omega$ - 10 $\Omega$ |
| Inductance of bagger coil ( $L_1$ )                     | 0.2818 H                 |
| Inductance of capsule coil ( $L_2$ )                    | 0.1 H                    |
| series resistance in the transmitting circuit ( $R_1$ ) | 1 $\Omega$               |
| series resistance in the receiving circuit ( $R_2$ )    | 1 $\Omega$               |



**Figure 6: General block diagram for S-S distance-based switch configuration.**

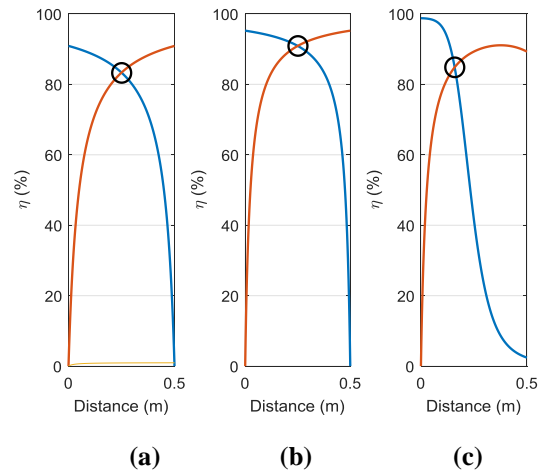


**Figure 7: The efficiency versus distance for the S-S Configuration at 8.2MHz resonance frequency, where: (a) High efficiency at low distance, and (b) High efficiency at high distance.**



**Figure 8: The S-S configuration indicating maximum efficiency at long distance is 90.91%.**

Fig. 9(a) illustrates Eq. (10) with the distance condition in Eq.(11), where the blue curve shows decreasing efficiency by increasing distance under condition of decreasing ranges of load resistance, and red curve shows increasing efficiency by increasing distance under condition of increasing ranges of load resistance. Two curves intersect at point at the middle distance between two circuits with intersected efficiency above 80%.



**Figure 9: The S-S distance-based switch configuration, where (a)  $R_L = 0 - 10 \Omega$  and (b)  $R_L = 0 - 20 \Omega$  for centimeter capsule coil which has radius in centimeter unit, and (c)  $R_L = 0 - 9 \Omega$ , and  $20 - 50 \Omega$ , for millimeter capsule coil which has radius in millimeter unit.**

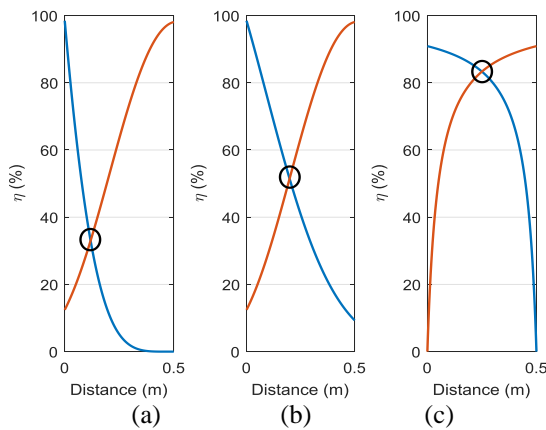
Fig. 9(b) improves intersected efficiency at the middle distance to be more than 90% by increasing load resistance range. Fig. 9(c) changes the capsule coil diameter to be in millimeter unit to reduce capsule endoscopy size but that results in decreasing efficiency. So, it should be compromise between overall system efficiency and capsule endoscopy size.

As shown in Fig. 8 and Fig. 9(a), at  $R_L = 0 \Omega$  to  $R_L = 10 \Omega$ , the minimum efficiency 83.33% has been obtained at a 0.25 m distance (middle of the distance between bagger and capsule circuits), while the efficiency increases to 90.91% at both the zero and maximum distance. As the range of load resistance increased to  $R_L = 0 \Omega$  to  $R_L = 10 \Omega$ , the minimum and maximum efficiency will be increased as shown in Fig. 9(b). In Fig. 9(b), the maximum efficiency 95.24% is obtained at the long distance is, whereas the intersection point that has high efficiency of 90.91% occurs at the middle distance between the two circuits.

Another very important parameter in the S-S distance-based switch configuration is the radius of the capsule coil. All the previous results of the high efficiency at short distances, intersection, and long distances results from the centimeter range of capsule coil radius, which is obtained by increasing the capsule size leading to difficulty in swallowing. So, the radius of capsule coil should be as small as possible such as in millimeter range, but that will affect the system efficiency and results in decreased system performance. Fig. 9(c) illustrates the two-intersection curve of S-S WPT at capsule coil radius is in the millimeter range which leads to small size of capsule than the previous two figures in which is smaller than the intersection efficiency for centimeter range coils. Therefore, there is a trade-off between the performance and capsule size. Fig. 9(a), and (b) which have the capsule coils radius in the centimeter range, while in Fig. 9(c) the obtained efficiency at the intersection point is around 85%, where the used simulation parameters of the millimeter capsule are given in Table 2.

**Table 2: The parameters of millimeter capsule.**

| Parameters                                 | Blue curve (high efficiency at zero distance) | Red curve (high efficiency at 0.5 distance) |
|--|---|---|
| Radius of bagger coil ( $a$ )              | 9 cm  | 50 cm                                       |
| Radius of capsule coil ( $b$ )             | 9 mm  | 9 mm  |
| Number of turns for bagger coil ( $n_1$ )  | 20 turns                                      | 30 turns                                    |
| Number of turns for capsule coil ( $n_2$ ) | 50 turns                                      | 50 turns                                    |
| Range of load resistance ( $R_L$ )         | 20 $\Omega$ - 50 $\Omega$                     | 0 $\Omega$ - 9 $\Omega$                     |
| Inductance of bagger coil ( $L_1$ )        | 500 $\mu\text{H}$                             | 1000 $\mu\text{H}$                          |
| Inductance of capsule coil ( $L_2$ )       | 100 $\mu\text{H}$                             | 100 $\mu\text{H}$                           |

**Figure 10: The P-P and P-S distance-based switch configuration, where (a) P-P, (b) P-P, and (c) P-S.**

### B. Distance-based Switch in the P-P and P-S configurations

In this section, we illustrated the performances of the proposed P-P, and P-S configurations of the WPT systems at both short and long distances as shown in Fig. 10, where Fig. 10(a) shows the efficiency versus the distance of the proposed P-P distance-based switch configuration.

In Fig. 10, it is noticed that the two curves are intersected at point that has very low efficiency, which is unreasonable in WPT systems. Therefore, by adjusting the load resistance we could be able to enhance the efficiency of the intersection point as shown in Fig. 10(a), and Fig. 10(b).

In the P-S configuration of the WPT system, the performance is better than the P-P configuration as shown in Fig. 10(c). As depicted in Fig. 10(c), the maximum efficiency at long distances was 90.91%, and at the intersection point was in the middle with efficiency around 83.33%. Finally, Table 2 concludes our results showing that the efficiency of the S-S distance-based switch is almost equal to the obtained efficiency using the proposed P-S distance-based switch at zero distance between the bagger and capsule circuits. However, at long distances, the S-S is the proposed WPT system achieved the highest efficiency compared to the others.

## IV. DISCUSSION

The results proved that the proposed DbSWPT is powerful to serve power for WCE dispense with the battery over traditional S-S WPT to overcome low efficiency with long distance between the bagger and the capsule coils. This can be achieved by using two potentiometers as be discussed previously. Compared to the state-of-the-art by Miah et al. [9], which achieved 20.4% system efficiency by using S-S configuration with 1050 KHz operating frequency, where the proposed system has better performance. Also, Fang et al. [7] achieved 26.14% with 8.2 MHz, the proposed system achieved superior performance. The used configuration in [9] included system parameters' settings as follows:  $L_1 = 63.6 \mu\text{H}$ ,  $L_2 = 19.3 \mu\text{H}$ ,  $n_1 = 11$  turns,  $n_2 = 50$  turns, series capacitance of bagger circuit is 330 pF, series capacitance of capsule circuit is 1240 pF, and the diameter of transmitting and receiving coils of 31 cm and 10 mm, respectively. By adjusting the operating frequency to 8.2 MHz, the system efficiency improved at short distances and deteriorated at the long distances. Accordingly, compared to our proposed system that adjusted the parameters' values and proposed automatic switch using distance conditions in Eqs. (10), and (11), which improved the system's efficiency over the complete distance of the capsule from the bagger through the GT track. This automatic switch switches from potentiometer 1 to potentiometer 2 as shown in Fig. 3. According to the measured distance, by a distance sensor, the potentiometer's value is changed as shown in Fig. 6(a) and Fig. 6(b). When the measured distance is less than 0.25 m, the potentiometer 1 is used, while when the measured distance is more than 0.25 m, the potentiometer 2 is used.

Moreover, the resonance frequency is a very important parameter in the WPT capsule endoscopy application, and the operating frequency that should be carefully selected to be safe on human body tissues as discussed previously in the methodology section. It is clear from the efficiency in Eq. (9) that the efficiency is directly proportional to operating frequency as shown in Fig. 11. Fig. 11 illustrates the efficiency versus the frequency at the following parameters: the radius of transmitted and receiving coils are 0.155 m and 0.005 m,  $n_1 = 10$  turns and  $n_2 = 50$  turns, respectively, and the load resistance  $R_L = 20 \Omega$ . Figure 11(a) shows the efficiency versus frequency at  $R_L = 1 \Omega$  using the same parameters.

Figure 11 shows that increasing the frequency results in increasing the efficiency. For example, as shown in Fig. 11(b), when the frequency is 1 MHz, the system efficiency is 23.76%, while at 7 MHz, the system efficiency becomes 85.96% and at 8.2 MHz, the system efficiency will be 87.24%.

In addition, Table 4 reports the state-of-the-art results on the WPT capsule endoscopy that cover the range of frequency from 1 MHz to around 20 MHz compared to the proposed system. The efficiency of the proposed system shown in Table 4 indicates to minimum efficiency of overall WPT system i.e. the efficiency of the intersected point at the middle of distance between bagger and capsule coils. In other words, the efficiency for distance less than 0.25 m is higher than this efficiency value and the efficiency for distance more than 0.25 m is also higher than this efficiency value. So, overall efficiency of designed WPT system in this paper is higher than any efficiency of other previous systems.

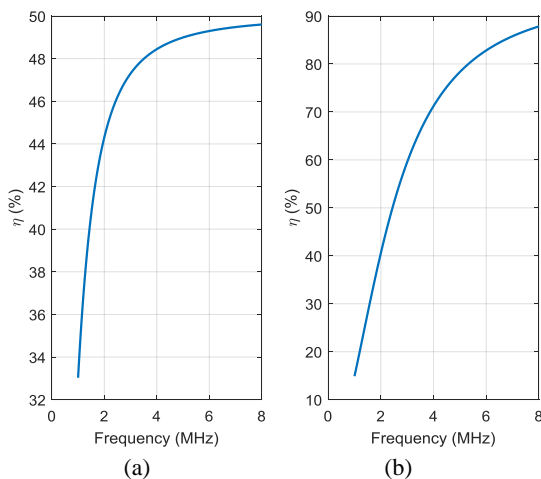


Table 3: Comparative between the two proposed WPT systems

| Configuration             | $R_2$       | $R_L$           | Efficiency at zero distance | Efficiency at 0.5 m distance | Efficiency at intersection point |
|---------------------------|-------------|-----------------|-----------------------------|------------------------------|----------------------------------|
| P-S distance-based switch | 10 $\Omega$ | 0 – 10 $\Omega$ | 50 %                        | 48.42 %                      | 33.33 %                          |
|                           |             | 0 – 20 $\Omega$ | 66.67 %                     | 61.8 %                       | 49.99 %                          |
|                           | 5 $\Omega$  | 0 – 10 $\Omega$ | 66.67 %                     | 65.46 %                      | 50 %                             |
|                           |             | 0 – 20 $\Omega$ | 80 %                        | 75.8 %                       | 66.66 %                          |
| S-S distance-based switch | 10 $\Omega$ | 0 – 10 $\Omega$ | 50 %                        | 50 %                         | 33.33 %                          |
|                           |             | 0 – 20 $\Omega$ | 66.67 %                     | 66.66 %                      | 50 %                             |
|                           | 5 $\Omega$  | 0 – 10 $\Omega$ | 66.67 %                     | 66.67 %                      | 50 %                             |
|                           |             | 0 – 20 $\Omega$ | 80 %                        | 80 %                         | 66.67 %                          |
|                           | 1 $\Omega$  | 0 – 10 $\Omega$ | 90.91 %                     | 90.91 %                      | 83.33 %                          |
|                           |             | 0 – 20 $\Omega$ | 95.24 %                     | 95.24 %                      | 90.91 %                          |

Table 4: Comparative study of the proposed systems and other state-of-the-art

| Ref.            | Year | Frequency (MHz) | Bagger coil diameter (cm) | Capsule coil diameter (cm) | distance (cm) | Efficiency   |
|-----------------|------|-----------------|---------------------------|----------------------------|---------------|--|
| [7]             | 2011 | 8.2             | 30×30                     | 1.2×1.2                    | 12            | 21.68%   |
| [14]            | 2015 | 16.47           | 16                        | 1.8                        | 7             | 32.43%   |
| [5]             | 2017 | 3.7             | –                         | –                          | 30            | 95.00%   |
| [9]             | 2019 | 1.050           | 31                        | 1                          | –             | 20.40%   |
| Proposed system |      | 8.2             | 60                        | 50                         | 50            | 90.91% - 95.25%<br>( $R_L = 5 - 10 \Omega$ )<br>95.25% - 90.91%<br>( $R_L = 10 - 5 \Omega$ ) |

Figure 11: System efficiency versus operating frequency for S-S configuration, where (a)  $R_L = 1 \Omega$ , and (b)  $R_L = 20 \Omega$ .

The two-intersection curve of S-S WPT when the capsule coil radius is in the millimeter range as shown in Fig. 9(c), resulting in a smaller capsule than in the previous two figures, where the intersection efficiency is lower than for centimeter range coils. As a result, there is a trade-off between performance and capsule size. Figures 9(a) and (b) show capsule coils with radius in the centimeter range, whereas Figure 9(c) shows an 85% efficiency at the junction site.

## V. CONCLUSION

To tackle WCE power challenge, this paper tries to redesign WPT system of WCE to remove the battery from it by using DbSWPT as discussed above. From result section, we improved the overall system efficiency. In this paper, we proved that the efficiency of WPT system is affected by the

distance between the bagger and capsule circuits. For traditional configurations, the efficiency is very poor at long distances as the coupling coefficient has very small value at 0.5 m distance. This paper tries to solve this problem by using a switching module that depends on a distance sensor which measures the distance between the bagger and capsule circuits to obtain better value of coupling coefficient at each distance between the two coils. In the proposed system, if the measured distance is less than a certain threshold distance one range of load resistance will be used and if the measured distance is higher than that threshold another range of load resistance will be switched on. The results showed that the threshold value occurs at the intersection point, which is adjusted to be at the middle of the whole distance, i.e., 0.25 m. It is proved that the P-P distance-based switch configuration has a very poor system efficiency whereas, the P-S configuration is asymptotic to system efficiency of S-S configuration. However, S-S is the preferred as it is a simpler configuration. Finally, the selection of system parameters is very important. For example, radius of capsule coil should keep as small as possible to be easy to swallow.

By increasing distance between two circuits compared to other searches, beside to use potentiometer as a load resistance, results in increasing the overall WPT system efficiency. Efficiency of S-S DbSWPT differs between 95.25% to 90.91% when load resistance differs from 10  $\Omega$  to 5  $\Omega$ , and differs between 90.91% to 95.25% when load resistance differs from 5  $\Omega$  to 10  $\Omega$ .

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