A Compact Receiving Side Circuit for Wireless Power Transfer with Foreign Object Detection Technique

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Abstract: Wireless power transfer is a promising technology, it is used to overcome the problems of conductive power transfer. However, numerous challenges still face this technology, especially in security issues. Detecting any foreign object in the proximity of the transmitter will save power and secure the system from any possible dangers. In this paper, A compact semi-active rectifier is proposed to detect foreign objects by applying the proposed control technique without extra components and also to control the charging process of the supercapacitor efficiently. Two different modes are proposed in this work to optimize power consumption. The low-power mode is used in the case of no receiver in the power transfer range or when a foreign object is detected, so the primary side controller adjusts the input voltage of the system to optimize the power consumption. Otherwise, it works in the power transfer mode at the resonance frequency.

1 INTRODUCTION

Suppling wireless sensor nodes is a critical issue, it can be powered using batteries where recharging and changing it requires a lot of effort, maintenance, and influences the environment if it is not disposed of properly. For that, other studies focus on energy harvesting with a super-capacitor to achieve the activation of the (WSN) for a certain period (Kanoun et al., 2021). However, the previous suggestions still face some lack to obtain sufficient power, especially for high-power WSN. Moreover, they are depending on environmental conditions, such as vibration and solar. Besides, for always-ON devices such as wake-up receivers WSN, the energy harvesting faces difficulties to maintain the required energy supply.

One of the alternative solutions is the inductive power transfer (IPT) systems, which deliver the required power and maintain their performances in harsh environments, such as water and dust even for movable devices. Optimizing the size of the receiver is also important. It is very useful to keep the size as small as possible due to the legibility to use WSNs with the minimum position constraints.

During the charging process of devices battery or supercapacitors, various challenges influence the system efficiency and the received power, such as the charging area (Bouattour et al., 2020), the detection of the receiver device (Bouattour et al., 2019), as well as the equivalent load that varies according to the state of the charge (Adawy et al., 2021). However, to achieve secure charging with sufficient output power and maximum possible power transfer efficiency, an accurate control technique should be used, especially for supercapacitors charging.

In fact, the supercapacitors have a proper amount of charges capacity with an ultra-low equivalent series resistance (ESR), which is considered as the main challenge for the charging process (Adawi et al., 2020) The low ESR causes to draw high transient charging current, especially at starting of the charging process when it is fully discharged. Practically, this high transient current can destroy power sources or at least switch off the system, which requires a constant current (CC) charging process. The CC charging can be reached by selecting a suitable compensation

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topology and designing a proper magnetic coupler. However, this method is not enough to force the system to work on the CC charging mode (Mai et al., 2021). Nonetheless, a closed-loop control technique is recommended to be applied for such systems in order to achieve secure charging. Typically, different techniques can be used to achieve CC charging. However, the duty cycle and phase shift angle of the used power converter can be adjusted based on the current sensor regardless of the amount of the load.

Another major aspect to consider is the detection of the valid receiver coil when it is situated in the proximity of the transmitter coil, which is called foreign objects detection (FOD). It helps to reach secure charging by forcing the transmitter side to work on the low power mode (Bouattour et al., 2020). In fact, in the case where a metallic object is situated on the top of the transmitter side, the magnetic fields of the sending coil will change (Shi et al., 2021), as well as, the object will be heated due to the generated eddy current (Shi et al., 2020). Moreover, the generated heating from metallic objects can also destroy the whole IPT system.

In this paper, the proposed control technique depends on the semi-active rectifier to achieve CC for charging the supercapacitor. Moreover, the semi-active rectifier guarantees that only permissible receivers can receive the power generated by the transmitter. An efficient FOD method based on the semi-active rectifier is also presented in detail. The sections of this paper are recognized as follows: In section 2, state of the art about FOD methods are introduced. However, in section 3, the problem statement and the proposed solution are introduced. In section 4, the proposed FOD technique is defined. The optimizing power technique is proposed in section 5. The experimental setup is discussed in section 6. Experimental results of the IPT system are discussed in section 7. The main conclusions are presented in section 8.

2 STATE OF THE ART OF FOD AND CC METHODS

The metallic objects can significantly affect the IPT system parameters such as the mutual inductance, equivalent impedance, and quality factor. These variations can be used in high-power applications to identify the receiver device. However, for low-power applications, it can be similar to the system behavior in the case of misalignment. This makes the process of detecting materials more challenging.

Detecting foreign objects can be achieved by different techniques, in (Hoffman et al., 2016), a temperature sensor is used to trigger an external light camera to sense any foreign object, while in (Bell et al., 2018), an ultrasonic sensor is proposed to detect the objects in proximity of the transmitter coil. These external sensors increase the cost of the system, consume more power, and require maintenance. Another technique supposes using an extra layer of coils to detect the foreign objects as demonstrated in (Zhang et al., 2019), however, this technique affect the IPT system parameters and has low accuracy to detect the metallic objects, especially for low-power applications

However, many studies focused on communication modules like Xbee and Bluetooth (Jung et al., 2021) to increase the ability to determine the permissible receivers. Meanwhile, the use of communication modules increases the power consumption, size, and cost of the receiver side circuit.

Others implement power line communication such as phase-shift keying (FSK) (Karimi et al., 2021), amplitude-shift keying (ASK) (Barbruni et al., 2021), and pulse density modulation (PDM) (Yenil et al., 2021) to transfer the desired data between primary and secondary coils.

Some modulation techniques influence the power transmission by the continuous fluctuations between connection and disconnection of the load, which can cause some damages and delay of charging. However, other searches use the detection by an external detection switch (Nutwong et al., 2019). These communication types show high performances to identify the receiver device with low power consumption and use the coil themselves. It can be implemented into the receiving side circuit before the rectifier stage based on additional switches connected to the receiving side circuit, as shown in Figure 1. Meanwhile, it increases the circuit cost and volume.

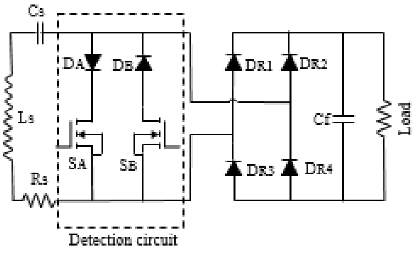

Figure 1: Block diagram of the system.

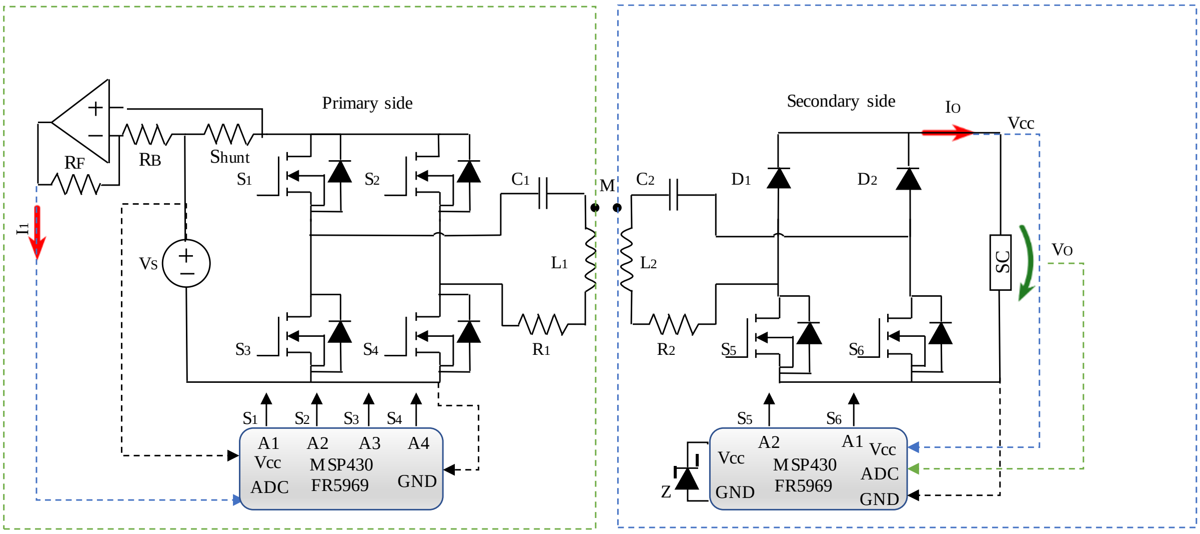

Figure 2: Schematic diagram of the proposed IPT system with control configuration.

On the other hand, for the secure charging of supercapacitors, the CC current techniques are required. Typically, various methods are proposed in research to achieve the CC during the charging process. This condition is important to increase the supercapacitor lifetime. In (Mai et al., 2021), an S-SP compensation topology is proposed to achieve the CC. However, the proposed solution is valid for no or just small misalignment conditions.

Other techniques use DC to DC converters after the bridge rectifier, as proposed in (Somsak et al., 2021), this method is not preferable in low-power applications, where both output power and power transfer efficiency can be highly affected because even for using efficient DC to DC converters, bridge rectifier consumes a lot of energy. Moreover, cost and receiver volume will be increasing. For that, in (Na et al., 2018), an active full-bridge rectifier is introduced to achieve the CC, although the use of DC to DC converters is not necessary in this case, a huge filter is required.

The more efficient converter which is named by the semi-active rectifier is presented in (Iam et al., 2020). However, using the semi-active rectifier allows the IPT system to dispense with using DC-DC converters, resulting in increased system efficiency and allowing to make direct power regulations without extra components. The output of the semi-active rectifier can be controlled by adjusting the duty cycle or by changing the phase shift angle between the pulses. Moreover, CC charging is also can be achieved even when the conducting angle equal to zero (Iam et al., 2020).

3 PROBLEM STATEMENT AND PROPOSED SOLUTION

Designing an optimal IPT system requires a low-power consumption with a secure power transfer and compact size. To address the drawbacks of the previous studies. A schematic of the proposed IPT system is illustrated in Figure 2, this paper proposes to use the semi-active rectifier on the secondary side for the following reasons:

1- The size of this converter can fulfill the compactness condition of the optimal IPT system.

2- It can be used to detect foreign objects by applying the proposed control technique without communication modules between the primary and the secondary side.

3- To increase the efficiency of the proposed IPT system, two different operating modes with high and low power are introduced. However, the IPT system selects the desired operation mode based on the semi-active rectifier.

4- CC during the charging process can be achieved even when the conducting angle is equal to zero.

Numerous advantages can be achieved due to using the semi-active rectifier. Compared to other DC-DC converters, a semi-active rectifier reduces the number of the used components, increases the system efficiency, and decreases the receiver volume and weight.

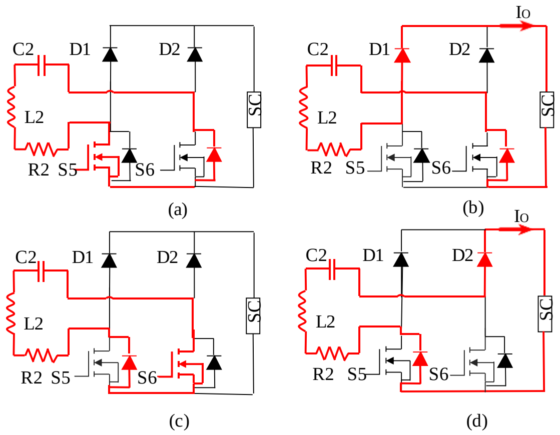

Figure 3: Operating modes of the semi-active rectifier. (a) Mode I, (b) Mode II, (c) Mode III, (d) Mode IV.

Fundamentally, various operating sequences can be used to control the output power of the semi-active rectifier. However, the operating modes of the proposed IPT system are depicted in Figure 3.

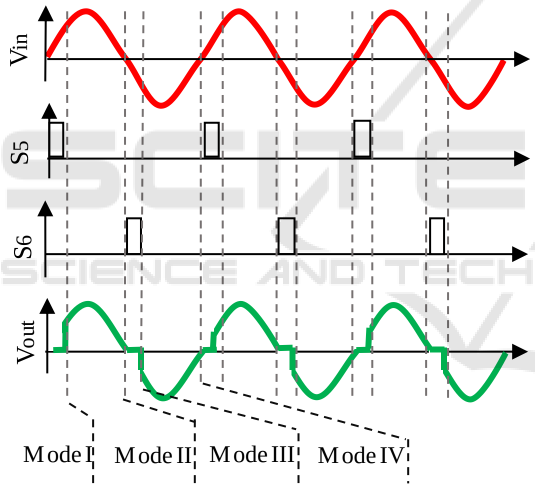

Figure 4: Proposed control operating waveform.

In Mode I, the current flows in the positive direction, switch S5 is on so the current will pass through this switch and the body diode of switch S6. However, in this mode, no current passes to the load. In Mode II, after the switch S5 is switched off, the current still flows through the diode D1 and the body diode of the switch S6. The supercapacitor will be starting to charge in this mode.

The current flows in the negative direction in Mode III, while switch S6 is on, the current will pass through it and complete its path through the body diode of switch S5. In this mode, the current stays in the resonant tank, and no current passes to the supercapacitor. In mode IV, switch S6 is switched off and the current can pass to the supercapacitor through the body diode of switch S5 and the diode D2. Moreover, the operating waveform of the semi-active rectifier is illustrated in Figure 4.

The proposed semi-active rectifier can be controlled by adjusting the duty cycle (D) of both switches in the range of (0-0.5). The root main square (RMS) of the resonant tank output voltage (Ve) is defined as Eq. 1.

$$Ve_{rms} = \frac{2\sqrt{2}}{\pi} D\, V_O \qquad (1)$$

4 PROPOSED FOD TECHNIQUE

For low-power applications, foreign objects in proximity of the transmitter side can significantly affect the IPT system parameters. To elaborate on these effects, the general equivalent circuit of the IPT system is illustrated in Figure 5.

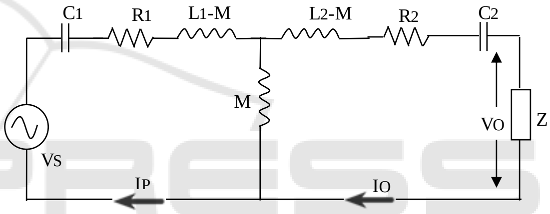

Figure 5: T-model equivalent circuit of an IPT system.

Where Vs is the input voltage, V_O is the output voltage, I_P, and I_O are the primary and secondary currents, respectively. R_1 is the resistance of the primary coil and R_2 is the resistance of the secondary coil, C_1 is the primary side compensation capacitor and C_2 is the secondary side compensation capacitor.

The mathematical model of the IPT system can be obtained by applying Kirchhoff's voltage law (KVL) as depicted in Eq 2 and 3.

$$V_S = \left(R_1 + j\omega L_1 + \left(\frac{1}{j\omega C_1}\right)\right) I_1 + j\omega M I_2 \qquad (2)$$

$$V_O = \left(R_2 + j\omega L_2 + \left(\frac{1}{j\omega C_2}\right)\right) I_1 + j\omega M I_1 \qquad (3)$$

A metallic object can be represented as an inductance with a series resistance, Meanwhile, it will decrease the equivalent inductance of the system and increase the equivalent resistance of it. This change can also affect the input current.

Typically, the input current can be measured either directly or using a differential amplifier and a shunt resistor in series with the power supply. In low-power applications, the input current range in the case of misalignment is overlapping with the case of the FOD, which increases the challenges. However, measuring the input current is not sufficient to detect foreign objects.

For such reasons, the controller of the secondary side is also should be programmed to detect the foreign object. Before transferring the power, the semi-active rectifier begins its work at a certain duty cycle (D=D1), at this moment the current sensor will measure the primary current value (Ip= I1) if the primary current is in the permissible range, the controller after 1 sec will change the duty cycle to (D=D2), and the primary current will be (Ip=I2). After 1 sec, the duty cycle will change to (D=D3) and the primary current will be (Ip=I3). However, this process is called a detection process, in case of a foreign object exists, the primary current will not be affected by the changes in the duty cycle (Ip=I1=I2=I3), in this case, the primary circuit will back to the low power mode. Otherwise, if the amount of current is changed, this means a permissible receiver exists and the power transfer process will begin

5 OPTIMIZING POWER TECHNIQUE

The proposed technique can optimize the consumed power at several bands. Firstly by getting rid of communication between primary and secondary sides. However, each part is required to control itself independently. To achieve this goal, two modes of operation that the primary side can work on are proposed. The first one is the power transfer mode and the second one is the low power mode. In the power transfer mode, electric energy can be transferred from the primary side to the load at a certain power level and under the resonance frequency. This process is valid only after making sure that there are no foreign objects in the proximity of the transmitter, as well as, a valid receiver is existing. In the low power mode, the minimum output power should be transferred to the secondary side. By decreasing the input voltage, leads to a decrease in the amount of output power.

From the previous equations, input power P_{in}, output power P_O, and power transfer efficiency η can be simply obtained, as illustrated in Eq. 4, 5, and 6.

$$P_{in} = \frac{V_{in}^2 (R_2 + Z)}{\omega^2 M^2 + R_1 (R_2 + Z)} \tag{4}$$

$$P_O = \frac{\omega^2 M^2 V_S^2 Z}{(R_1 (R_2 + Z) + \omega^2 M^2)^2} \tag{5}$$

$$\eta = \frac{\omega^2 M^2 Z}{R_1 (R_2 + Z)^2 + \omega^2 M^2 (R_2 + Z)} \tag{6}$$

Both input power, as well as output power, are related to the square of the input voltage. For that, input and output power will be decreased when the input voltage decreases. Moreover, the power transfer efficiency doesn't be affected by the amount of input voltage. The flow chart of the control procedure is illustrated in Figure 6.

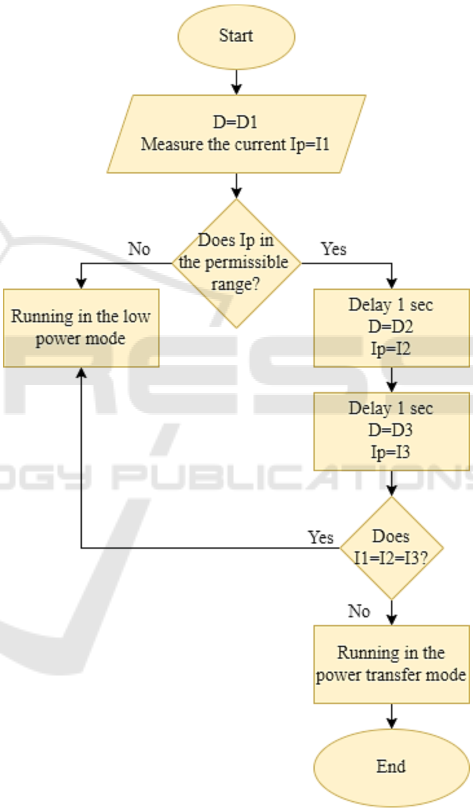

Figure 6: Flowchart of the proposed control.

6 EXPERIMENT SETUP

The experimental prototype of the proposed IPT system is illustrated in Figure 7. Moreover, the main components and system parameters that are used in the experiment are depicted in Table 1.

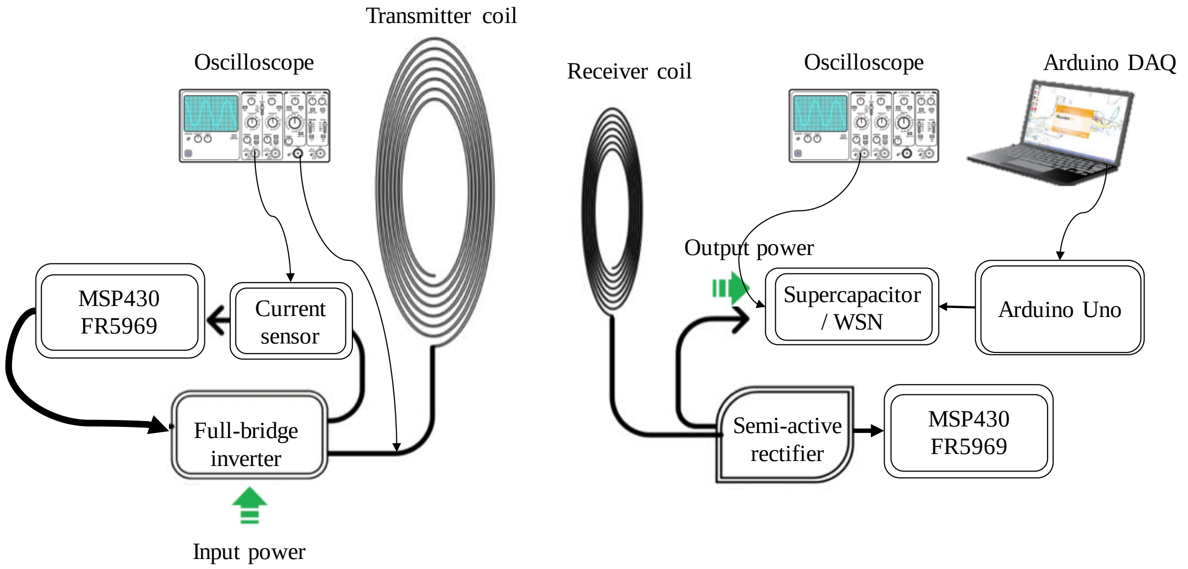

Figure 7: Experimental prototype of the proposed IPT system.

Table 1: System parameters.

Parameters	Values
Operating frequency	100 kHz
Voltage input	5 V
Coupling factor	0.6
Primary coil inductance	10 uH
Primary coil resistance	0.3 Ω
Secondary coil inductance	10 uH
Secondary coil resistance	0.1 Ω
Compensation capacitors	253.3 nF
Switches (S1-S6)	IRLZ44
Diodes (D1, D2)	UF4001
Supercapacitor	3 F, 5 V
Amplifier	LM324
Controller	MSP430FR5969

On the primary, side an MSP430FR5969 controller is used to generate the pulses that are used to operate the full-bridge inverter. Typically, MSP430FR5969 is used to generate the desired operating frequency. Another reason to use the controller is to move between the low power mode and the transfer power mode. However, adjusting the duty cycle of the output pulses changes the amount of generated voltage.

A current sensor based on an LM324 differential amplifier is used to measure the input current due to its high gain, wide power supply range, very low consumes power, and low input offset voltage and current.

On the secondary side, the semi-active rectifier is controlled by the MSP430FR5969 controller, the mean reason for selecting this controller exactly is the amount of consumed power compared to other controllers. It consumes power ten times less than other controllers (Gotz et al., 2020), where this purpose is very important on the secondary side, a 3.3 V Zener diode is used to protect the controller from any voltage variations.

It should be noted that even with the input voltage of the secondary side less than 3.3 V, the semi-active rectifier will work as a passive rectifier and the supercapacitor can be successfully charged. However, the FOD technique can be effective after the controller is supplied. The output voltage is continuously monitored by the controller, a voltage divider circuit is necessary also to prevent the malfunction of the controller.

Selecting the supercapacitor size is depending on the application, the system parameters, and the availability of charging time. Typically, the size of the supercapacitor $C_{storage}$ can be calculated based on Eq. 7.

$$C_{storage} > 2E_{WSN}(V_{high}^2 - V_{low}^2)/\eta_{WSN} \quad (7)$$

Where E_{WSN} is the energy of the WSN, V_{high} and V_{low} are the upper and lower threshold of the supercapacitor, respectively. η_{WSN} is the WSN efficiency.

The DAC software is also used to collect some data from the IPT system like the detection behavior and charging times in different cases, it needs an Arduino controller connected with a PC.

7 RESULTS AND EVALUATION

To evaluate the proposed IPT system, different cases are tested: no object or receiver, valid receiver, and foreign object in the proximity of the transmitter. Moreover, the same experiments are repeated with misalignment between the coils to investigate the output results under this condition.

The generated pulses of the secondary side controllers are illustrated in Figure 8. The pulses are generated to satisfy the control method requirements, the duty cycle for both switches is changed during the detection mode.

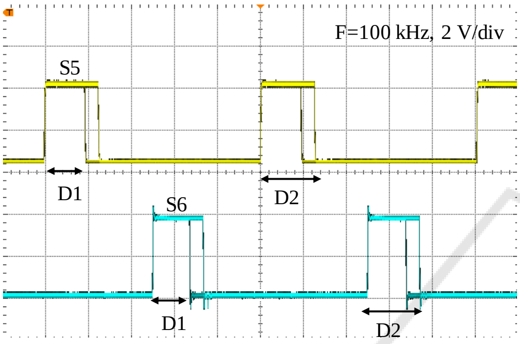

Figure 8: Semi-active rectifier switches during the duty cycle changes.

Initially, when no receiver coil or a foreign object is in the proximity of the sending side, it is operated in the low-power mode, any variation of the input current triggers the controller to work on the power transfer mode and the detection mode will be starting. Figure 9 illustrates the input current behavior in different modes.

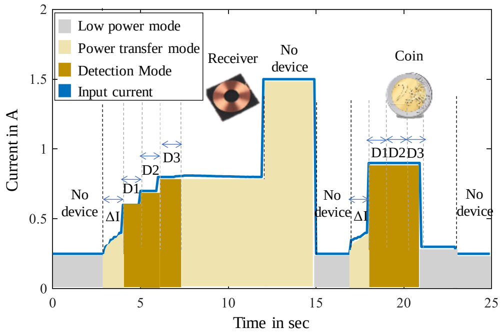

Figure 9: Input current at different conditions.

In the first three seconds, the proposed system was working on the low-power mode, the amount of the input current is 0.25 A, then the receiver coil is located in the proximity of the transmitter, for that, the input current is changed and the mode of operation is moving to the detection mode, variations of the duty cycle during three seconds are enough to increase the current from 0.6 to 0.8 A, resulting in the detecting of the receiver then the power transfer is starting with around 0.82 A. After three seconds, the receiver is removed and the operation mode is still in the power transfer mode, so the current increases to 1.5 A. When the input current is equal to the no-load current for three seconds the system moves to the low power mode. Per second 17, a 2 euro coin is situated in the proximity of the transmitter. Input current is varying and the operation mode is moved to the detection mode. It's obvious from the figure that the variation of the duty cycle didn't change the amount of the input current, it is fixed around 0.9 A, so the system is moved to the low power mode. Moreover, per second 23, the foreign object is removed and the system is still in the low-power mode.

The same procedure is repeated with a misalignment of 8 mm between the transmitter and receiver, the result is demonstrated in Figure 10.

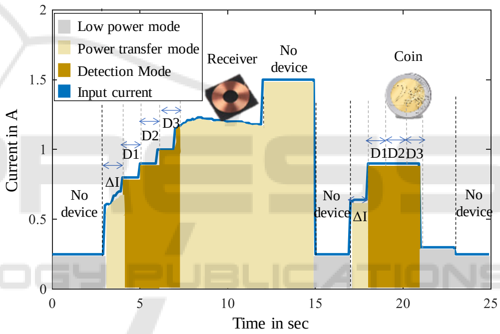

Figure 10: Input current at different conditions with misalignment.

The only difference between the two cases is what happens during the transfer of the power to the receiver coil. The input current in the power transfer mode increases from 0.8 to 1 A in the detection mode and around 1.2 A in the power transfer mode. Moreover, when the coin is in the proximity of the transmitter, the same behavior of the no-misalignment case is formed.

The supercapacitor takes around 40 sec to be fully charged in the case of no-misalignment, the output current is around 330 mA, it is obvious from the figure that the current is almost constant during the charging process. However, 17 sec are required to get the controller desired voltage, this means, the FOD method can start working after this period.

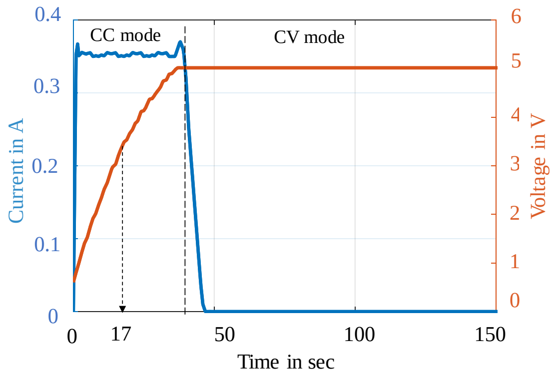

Figure 11: Charging current and voltage with no misalignment.

An 8 mm misalignment between the coils is also considered, in this case, the supercapacitor requires 150 sec to complete the charging process, while the current charging is 90 mA. The CC of charging also exists even with this amount of misalignment. However, the 3.3 V can be obtained after 32 sec, where the controller can start to detect foreign objects, as illustrated in Figure 12.

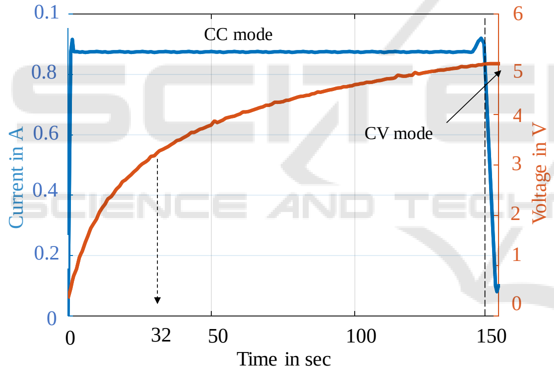

Figure 12: Charging current and voltage with an 8 mm misalignment.

Typically, the consumed power level depends on the used WSN and the mode of operation. For example, WSN based on ARM Cortex-m3 microprocessor consumes 500mW with 5V in active power mode and 80PW in sleep power mode. In this case, the proposed system can supply the WSN continuously in the sleeping mode and more than one minute in the active power mode per charge. However, it is considered very well because the charging time is about 40sec with no misalignment between the coils and about 150sec in the worst case. The power supplying time will be changed if another type of WSN is used. A lot of WSN's consume much less power than the ARM Cortex-m3.

8 CONCLUSIONS

This paper introduced an IPT system with a communication-free between the primary and the secondary sides. An efficient semi-active rectifier is controlled by the proposed method to charge supercapacitors, especially for WSN applications. Both analytical and experimental results show that the proposed control technique success to detect foreign objects in the proximity of the transmitter side. Optimizing the power consumption is also considered using two different types of operation mode; power transfer mode and low-power mode. In the case of no receiver detecting or foreign object existing in the proximity of the transmitter, the primary side controller decreases the input voltage by adjusting the duty cycle, resulting in activating the low-power mode. Compared to other studies, the proposed system has many benefits, such as compactness, sensorless, communication-free, and the security of charging. These benefits give a great advantage to using the proposed technique instead of other limited ones.

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