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Efficiency of Wireless Power Transfer System with PWM Methode as Rectifier on Receiver

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Abstract

One part of the wireless power transfer system is rectifier, where the energy which received by the receiver conditioned according to the device character. While devices with direct current as a wave form of electrical energy is commonly used. Conventional rectifier was using half wave or full wave circuit where uses diode circuit, capacitor and transformer as filter. The disadvantage of the system is reactive power and harmonization. We proposed the pulse width modulation because PWM could enhanced power factor value on an AC voltage source system with 50 Hz frequency. The main focus on which this study was based was to derive efficiency values from pulse width modulation utilization in the rectification process while the frequency work at 5 MHz and highest power at 54.48 Watt, and compare this reasearch with published research for similar systems. To achieve the objectives of this study then performed design and build system, measurement and analysis of the value of system efficiency. The results of the research obtained the highest value of efficiency at 81%.

Keywords: *wireless power transfer, PWM methode, rectifier, efficiency system*

1. Introduction

One part of the system is the power conditioning where after the energy is received by the receiver, the condition of the power needs to be adjusted so it can be well received by the load. The main focus on this paper is to find the effectiveness and efficiency of the system. One of the most important part in the process of energy transferring is the power conditioning on the receiver, where the energy that is gotten from the transmitter ought to be proceed by the power conditioning so it is suited with the ideal load specification which will be used. There are several previous works that tried to find the highest value of rectifier on the receiver. Moh et al [1] in their work used system buck converter in the rectifier system and obtained 84.6% efficiency. Riehl et al [2] employed synchronous rectifier and obtained 84.6% while Nga et al [3] with bootstrapping method obtained 76% efficiency. Kim et al [4] with full bridge rectifier obtained 80%. Rectifier in receiver has the same purpose with the general rectifier. The rectifier in receiver system of wireless power transfer is required to change AC to DC, Conventional rectifier design for AC to DC conversion was using half wave or full wave circuit where uses diode circuit, capacitor and transformer as filter. The disadvantage of the system is reactive power and harmonization [5]. Georgakas et al proved in their publication that PWM could enhanced power factor value on a AC voltage source system with 50 Hz frequency [6]. The transistor of PWM has high cut off frequency and low dissipating power on rectification process. In this paper, we propose to employ a PWM method on power conditioning as a rectifier in the receiver of wireless power transfer.

2. Research Method

A design of wireless power transfer system can be seen in Figure 1 where the transmitter sends the energy out to the receiver using two induction coils L_1 and L_2. The coupling between the transmitter and receiver is described by a mutual induction M or can be characterized by the coupling factor k. The relationship between the mutual induction M and the coupling factor is as follows

$$M = k\sqrt{L_1 L_2} \quad (1)$$

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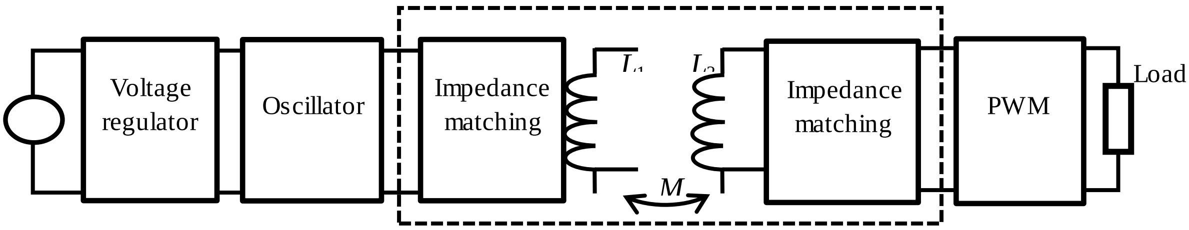


Figure 1. Block Diagram of Circuit Implementation PWM Rectifier on Receiver [4]

In the following we concentrate our observation to the circuit part inside the dashed bracket as illustrated in Figure 1. The oscillator block as a source delivers the voltage V_1 to the impedance matching circuit and then to the coupling structure. The coupled energy will be conditioned by the impedance matching circuit on the receiver side, and delivered to the PWB block and Load. The PWM block and load is modeled by resistor R_2.

Figure 2 shows the equivalent circuit of the coupling structure (circuit inside the dashed bracket in Figure 1). R_1 describes the resistance of the source and any losses in the transmitter side, whereas, C_1 and L_1 model the impedance matching circuit and the coupling coil. The coupled energy from the transmitter side to the receiver side is defined as a current-controlled voltage source $j\omega M\, I_1$. The load and all losses in receiver side are characterized by R_2, While C_2 and L_2 model the impedance matching and the coupling coil. The feedback from the receiver side to the transmitter side due to the current flowing in the receiver circuit is described by another current-controlled voltage source $j\omega M\ I_2$. This current-controlled voltage source according to the theorem of equivalent circuit can be observed as the load seen from the transmitter.

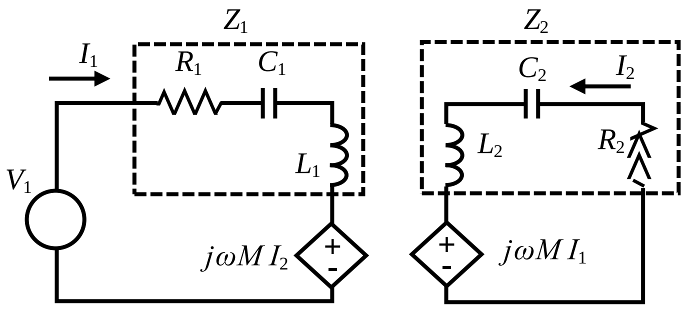


Figure 2. Equivalent circuit of the coupling structure in Figure 1

The load seen from the transmitter side to the receiver, Z_{TR} can be derived as follows

$$Z_{TR} = \frac{j\omega M\ I_2}{I_1} = \frac{j\omega M\left(-\frac{j\omega M\ I_1}{Z_2}\right)}{I_1} = \frac{\omega^2 M^2}{Z_2}$$

Here, we use $Z_1 = R_1 + j\omega L_1 + 1/(j\omega C_1)$ and $Z_2 = R_2 + j\omega L_2 + 1/(j\omega C_2)$ as total impedance in transmitter side and receiver side, respectively. With equation (1) we can give the equivalent load impedance as function of the coupling factor k

$$Z_{TR} = \frac{\omega^2 k^2 L_1 L_2}{Z_2} \tag{2}$$

In this wireless power transfer system, we are interested in delivering the power to the load maximally, which can be achieved by fulfilling the following condition [8]

$$Z_1 = Z_{TR}^* \quad \rightarrow \quad Z_1 = \frac{\omega^2 k^2 L_1 L_2}{Z_2^*}$$

By slightly modification we come to

$$\frac{Z_1}{j\omega L_1} = k^2 \left(\frac{j\omega L_2}{Z_2}\right)^*, \tag{3}$$

The condition can be furthermore represented as Q_1 and Q_2

$$k^2 = \frac{1}{Q_1 Q_2^*}, \tag{4}$$

which

$$Q_1 = \frac{j\omega L_1}{Z_1}, \quad \text{and} \quad Q_2 = \frac{j\omega L_2}{Z_2} \tag{5}$$

Figure 3 shows the magnitude of Q_1 and Q_2 as function of the frequency. In order to get the condition of maximally transferred power, the curves must touch or intersect to each other. It is desirable that both the transmitter and the receiver have the same resonant frequency, so that the curves of the magnitude of Q are aligned, as shown in Figure 3.

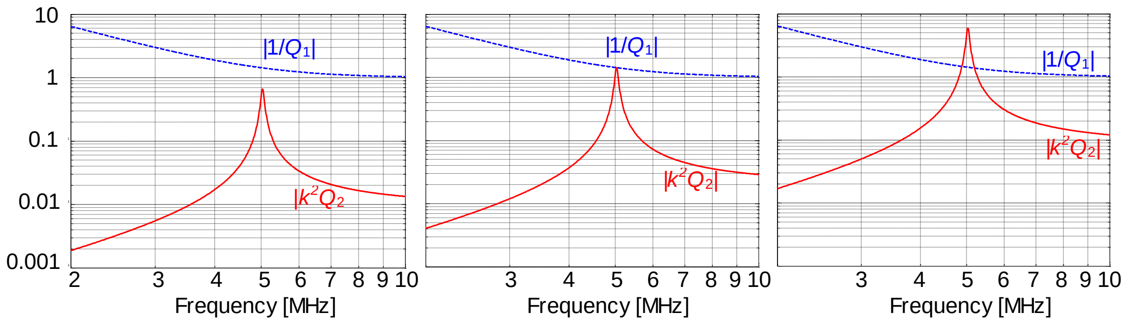


Figure 3. Q-Tip Diagram for R_1=225 ohms, R_2=2.4 ohms, L_1=L_2=5 μH, C_1=C_2=200 pF and the coupling factor a) k=0.1, b) k=0.147 (critical coupling), c) k=0.3

The value of Q_1 and Q_2 depends only on the serial impedance Z_1 and Z_2 and on the frequency, so that for given component values the blue dashed curve 1/Q_1 in Figure 3 is fixed. On the other hand, the red solid curve k^2Q_2 is also a function of the coupling k. The value of the coupling factor depends on the separation of the transmitter and receiver. If the receiver is close to the transmitter, the coupling factor has a large value, the curve k^2Q_2 has bigger value than 1/Q_1 at the resonant frequency. The curves intersect at two different points. This condition is called over-coupled, which is illustrated in Figure 3c. By enhancing the distance between the transmitter and the receiver, we reduce the coupling factor to certain value, so that the curves touch at a point. This condition is a critical coupling, and the coupling factor is called as critical coupling factor k_c. This special case is depicted in Figure 3b. If the separation between the transmitter and the receiver is far enough, the coupling factor takes enough small value, the curves have no intersection. The circuit can transfer the power maximally. The condition is shown in Figure 3a, which is called under-coupled.

The transmitter consists of an oscillator which based on Rover model [8]. The 200pF capacitance and the 5 μH inductance will be put on the circuit so they can produce a resonance at around 5 MHz. The transmitter circuit is depicted in Figure 4. Overall, the circuit is formed by a capacitor of 200 pF, an inductor with air core 2.5 uH as a choke, a disk-shaped coil as coupling element of 2.5 μH, two resistors of 10k ohm, two resistors of 460 ohm, two Zener diodes 10 V, two diodes, an IC of type LM7812, two transistors IRF 2007. The transmitter circuit can generate high frequency signal with a resonant frequency of 5 MHz.

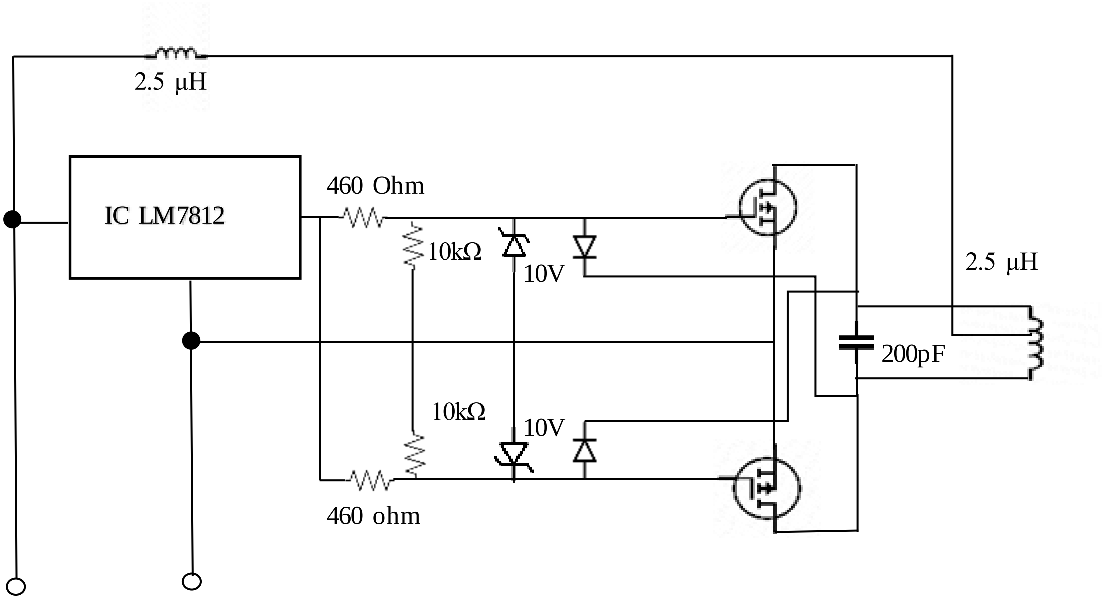


Figure 4. Transmitter Part

With the loop equation, the voltage at the inductor can be calculated by,

$$V_L = L\frac{di_s}{dt} = V_S(t) - V_{AFE} = V_S(t) - \alpha V_0 \quad (6)$$

The constant α can take the value 1, -1, or 0, as described before. If α=1, the inductor value has the negative value, which means the inductor current i_S decreases with the time. For α=-1, the inductor value will be positive, the inductor current increases. For the case α=0, the inductor current can increase or decrease its value depending whether V_S has positive or negative value during the time. This condition allows the full control of the current.

On the receiver, rectifier will be used on PWM method after the impedance matching circuit. The rectifier converts AC to DC while during the process, the power loss needs to be reduced on every block, so that the conversion process needs to be made more efficient. In order to process the multi pulse on PWM system we will employ several field effect transistors and RC circuit to control the output voltage. The so-called bridge-connected PWM circuit is shown in Figure 5.

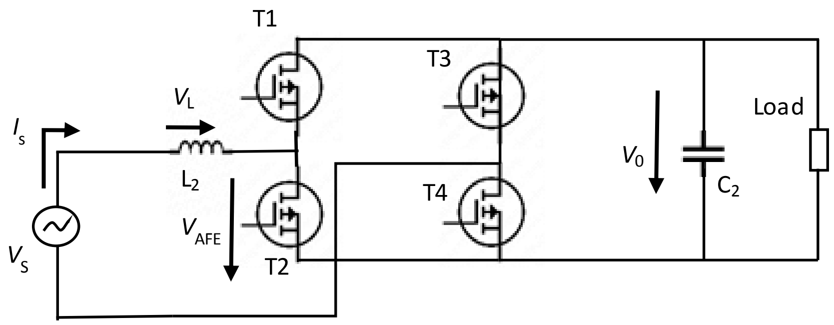


Figure 5. PWM Rectifier Scheme [5]

The scheme in Figure 5 can be driven in unipolar or in bipolar condition. During the positive half cycle of the input signal, T_1 and T_4 are forward biased, whereas T_2 and T_3 are reverse biased. When these are triggered or fired, the transistors T_1 and T_4 start conducting so that load current flows through them. The voltage at the load V_0=V_{AFE}. On the other hand, during the negative half cycle of the input AC, T_2 and T_3 conducts, T_1 and T_4 are reversed biased. The load current flows through T_2 and T_3. The voltage at the load V_0=-V_{AFE}. Principally, there is a third condition, T_1 and T_3 conduct, where T_2 and T_4 are reverse biased, or T_2 and T_4 conduct and T_1 and T_3 are reverse biased. The voltage V_{AFE}=0. With the component values in transmitter and receiver, we can calculate the critical coupling factor k_c of the circuit according to eq. (4). For both transmitter and receiver we got, L=5 µH, C =200pF, f=5.033MHz and R_1=225 ohm and R_2=2.4 ohm, so that,

$$X_L = 2\pi fL = 158.114 \text{ ohms}, X_C = 1/(2\pi fC) = 158.114 \text{ ohms},$$

$$Q_1 = \frac{2\pi fL}{\sqrt{R_1^2 + (X_L - X_C)^2}} = \frac{158.114}{225} = 0.7027$$

$$Q_2 = \frac{2\pi fL}{\sqrt{R_2^2 + (X_L - X_C)^2}} = \frac{158.114}{2.4} = 65.8808$$

$$k_{cr} = \frac{1}{\sqrt{Q_1 Q_2}} = 0.147$$

Figure 6 shows the receiver part of the wireless power transfer system under consideration. Here we put a coil L_1 and a capacitor C_1 in parallel instead of a voltage source. The receiver circuit consists of L_1=2.5µH as spirale-disk coil, L_2=2.5µH coil with air core, C_1=200pF, C_2=200pF, and T_1, T_2, T_3, and T_4 are MOSFETs.

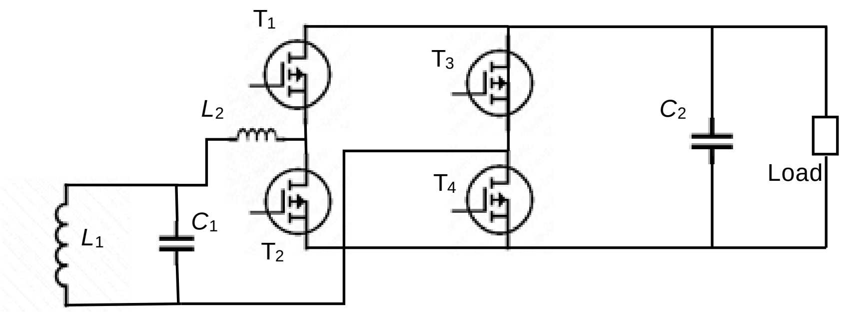


Figure 6. Receiver Part with PWM

After fabricating the circuit, the voltages and currents in transmitter and receiver circuits measured under certain conditions. Figure 7 shows the measurement process. We define several important quantities to be measured,

In transmitter side:

a) V_{trans}=Transmitter Voltage (volt)
b) I_{trans} =Transmitter Current (ampere)
c) I_{tb} =Transmitter Current without load from Receiver part (ampere)
d) P_{trans}=Transmitter Power (watt)
e) P_{tb} =Transmitter Power without load from Receiver part (watt)

In receiver side:

a) V_{trans}=Receiver Voltage (volt)
b) I_{rec} =Receiver Current (ampere)
c) I_{load} =Load Current (ampere)

d) P_{rec} =Receiver Power (watt)
e) P_{load} =Load Power (watt)

Figure 7. Measurement process

3. Results and Analysis

By measuring the voltage and current, the power can be calculated in both transmitter and receiver sides. Then, the efficiency can be determined by comparing the received power and the sent power. By calculating each power from the transmitter and receiver, we can find the value of its power efficiency, where:

$$P_{trans}=V_{trans} \cdot I_{trans}$$

$$P_{rect}=V_{rect} \cdot I_{rect}$$

$$Efficiency = \frac{Prect}{Ptrans} .100\ \%$$

Table 1 gives the measured voltages and currents and the respective calculation of the powers and efficiencies. From the measurement on the transmitter and receiver, it shows the highest efficiency value of 81% for the distance between transmitter and receiver 1 cm and lowest 4% for 15 cm.

Table 1. Measurement results

	Transmitter					Receiver							
d (cm)	Vtrans (V)	Itrans (A)	Itb (A)	Ptrans (W)	Ptb (W)	Vrec (V)	Irec (A)	Iload (A)	Prec (W)	Pload (W)	µS (%)	µM (%)	µPWM (%)
1	13.6	4	3.4	54.5	46.2	10.5	4.2	3.5	44.1	36.4	81%	95%	83%
2	13.6	3.4	2.8	46.3	38.1	10.2	3.4	3.1	34.7	31.7	75%	91%	91%
3	13.6	3.2	2.6	43.6	35.4	10	3.2	3.1	32.1	31.1	74%	91%	97%
4	13.6	3	2.4	40.9	32.7	9.8	2.9	2.7	28.4	26.5	70%	87%	93%
5	13.6	3	2.4	40.9	32.7	9.5	2.7	2.5	25.7	23.8	63%	79%	93%
6	13.6	2.8	2.2	38.1	30	9.2	2.6	2.5	23.8	22.9	62%	79%	96%
7	13.6	2.5	2.2	34.1	29.9	8.3	2.5	2.3	20.8	19.2	61%	70%	92%
8	13.6	2.5	1.9	34.1	25.9	7.4	2.4	2.3	17.6	16.9	52%	68%	96%
9	13.6	2.5	1.9	34.1	25.9	7.3	2.3	2.1	16.7	15.3	49%	65%	91%
10	13.6	2.3	1.7	31.3	23.2	6.7	2.3	2.1	15.4	14.1	49%	66%	91%
11	13.6	2.3	1.7	31.3	23.2	6.5	2.1	1.7	13.7	11.1	44%	59%	81%
12	13.6	2	1.4	27.2	19.1	6.3	1.7	1.5	10.7	9.4	39%	56%	88%
13	13.6	1.5	0.9	20.4	12.3	4.2	1.4	1.1	5.8	4.6	29%	48%	79%
14	13.6	1.5	0.9	20.4	12.3	3.5	0.9	0.6	3.2	2.1	15%	26%	67%
15	13.6	1.4	0.8	19.1	10.9	2.8	0.3	0.2	0.8	0.6	4%	8%	67%

First of all, we did measure the current flowing in the transmitter without the feedback from the receiver, it was 0.6 A, so we can calculate the pure current sent to receiver, with real current (I_{tb}), for the distance d=1 cm we get

$I_{tb} = I_{trans}$–0.6A=4 A–0.6A=3.4A

with this current I_{tb} and the voltage V_{trans} we can calculate the power sent from the transmitter to receiver and power absorbed by the load.

$P_{tb}=V_{transmitter} x I_{tb}=13.6V x 3.4A=46.2W$

In the same way, the received power can be calculated by multiplying the current and the voltage at the receiver,

$P_{rec}=V_{rec} x I_{rec}=10.5V x 4.2 =44.1W$

So, the coupling factor can the be determined by

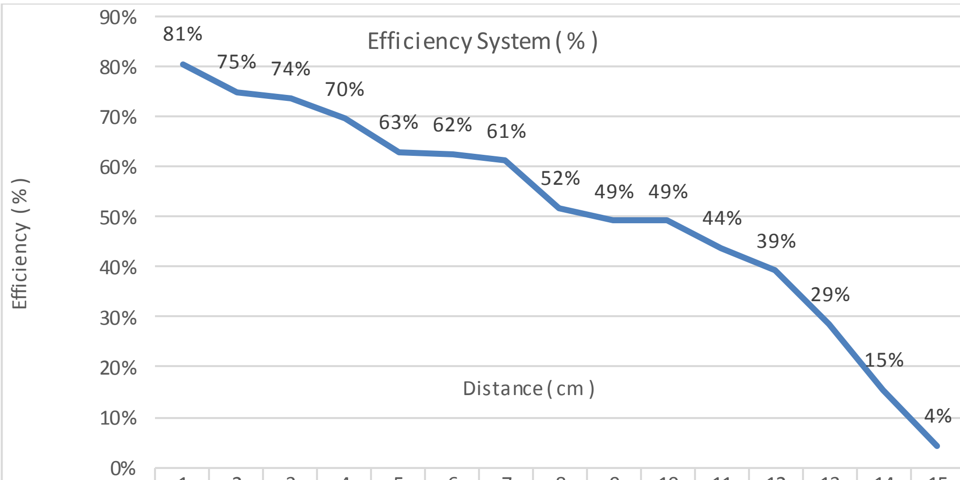
$$k = \sqrt{\frac{Preceiver}{Ptb}} = \sqrt{\frac{44.1}{46.2}} = 0.98$$

With kc=0.147 and k =0.98, that mean $k>kc$, and satisfying the over-coupled criteria, in which the system is eligible to transmit energy at maximum conditions. And for power loss on mutual induction process is equal,

$P_{Mloss}=P_{tb}–P_{rec}=46.2W–44.1W=2.1W$

The voltage at the transmitter is not affected by the distance between the transmitter and the receiver. It is unchanged at the value 13.6 Volts. The current in the transmitter was affected by the distance between the transmitter and the receiver. The highest current, 4 Ampere, was obtained for 1 cm and the lowest current, 1.4 Ampere, was obtained for 15 cm. The measurement on the receiver showed, that both voltage and current are influenced by distance. The highest voltage and current are 10.5 Volts and 4.2 Ampere, obtained for 1 cm, and the lowest are 2.78 Volts and 0.3 Ampere at the farthest distance 15 cm. The rectification process requires the power caused by the dissipation effect, and the value of the system efficiency has calculated by this research.

Figure 8 and Figure 9 give the efficiency of the system and the efficiency of the PWM obtained by varying the distance between the transmitter and the receiver. The curves can give the guidelines for the designers to choose the optimal distance for their applications. Table 2 shows the comparison the reported work and previous researches.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
µS(%)	81%	75%	74%	70%	63%	62%	61%	52%	49%	49%	44%	39%	29%	15%	4%

Figure 8. Efficiency as function of the distance between the transmitter and the receiver

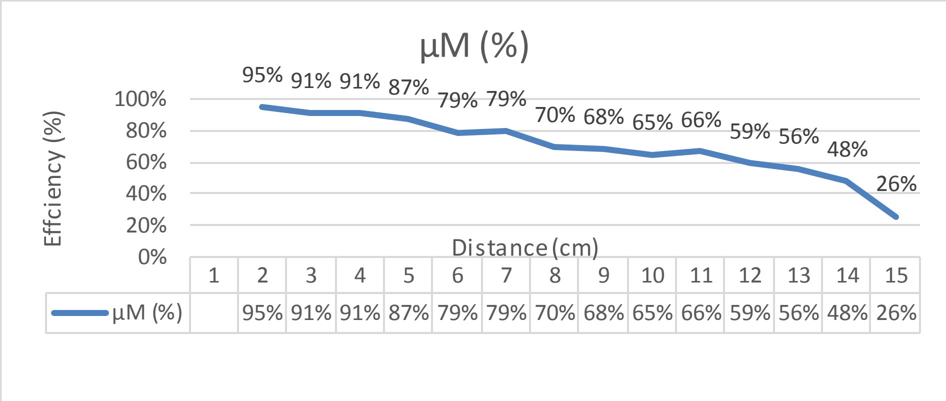


Figure 9. Efficiency for Mutual induction system as function of distance between the transmitter and the receiver

Table 2. Comparison between previous researchs

Paper	Year	Transfer Methode	Rectifier Methode	V_{Max} (V)	$P_{Out,max}$ (W)	Freq	Efficiency (%)
[1]	2015	MI *)	Buck Converter	25	6	6.78 MHz	84.6%
[2]	2015	MI	Syncronous Rectifier	3	2.5	128 kHz	80 %
[3]	2014	MI	Bootstrapping and ADDLL	12	3.8	6.78 MHz	76 %
[4]	2014	MI	Full Bridge with MCU and FSK	12	50	1.78 MHz	80 %
This work		MI	PWM	13.62	54.48	5 MHz	81 %

*) MI: Mutual inductance

4. Conclusion

PWM as rectifier is presented in this paper. The transmitter formed from voltage regulator, royer oscillator, and impedance matching circuit. The receiver formed from Impedance matching circuit, RL Filter and PWM rectifier with 4 MOSFET that formed bridge circuit. The system obtained the highest efficiency, 81% at 1 cm distance and the lowest efficiency, 4% at 15 cm distance. The rectification process requires the power caused by the dissipation effect, and the value of the system efficiency has calculated by this research.

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