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On the impact of variable in wireless power transfer system using a robust design method

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ABSTRACT

Our purpose is to consider Wireless Power Transfer (WPT). WPT is the transmission of electrical energy without wires as a physical link. Strategic development of the WPT is based on statistical analysis using the Taguchi method. The purpose of the Taguchi method in this work is to reduce the number of experiments in WPT. WPT is a process of transmitting electrical energy from one point to another point without using cables. Several parameters have been identified to perform WPT which includes input voltage, inductor, size of cable and capacitor. Statistically, to produce all of the parameters with an example of four parameters will require 256 numbers of experiments. Referring to the Taguchi method in the array orthogonal, the number of experiments is reduced to 16 experiments. The cost of the experiment can be reduced based on the analysis by Taguchi method. In this experiment, the WPT will be elaborated based on the distance and amount of power. The light of 5V led light is used as an indicator in this experiment. The technique using in the WPT system is an inductive coupling.

1. Introduction

Wireless Power Transfer (WPT) is a process of transferring power between two points without using a physical wire or cable. Nowadays, most of electrical transmission uses solid core inside the electrical insulator. However, power is lost if the wires damaged or disconnected. The benefits of WPT technology are that the transmission process is safer as WPT use electro-magnetic field to transmit energy instead of hanging wire as seen in a common electrical transmission system. The hanging wire is dangerous if any passive object link from life to neutral because it can create a link of electrical sources. WPT uses an electro-magnetic field (EMF) to generate electricity, so it is different with the physical wire concept. In fact, the maintenance of this technology is easier and the cost is cheaper for the maintenance job should be done at certain places only. Indirectly, this method can be an alternative to prevent cable from being stolen. Research on the WPT is still small in number and its application in real life is still limited. Intensive research is needed to be explored since the contribution in this field has been huge. Many researchers have explored using many parameters in WPT but from the observation, many researchers did not utilize the parameter with maximum performance (Sample et al., 2011; Sample and Smith, 2009; Low et al., 2009; Chen et al., 2010; Imura et al., 2009).

To test and identify all parameters took a longer time and cost, so Taguchi method is approached. Taguchi method is a tool in statistical to reduce the number of experiments which can identify most significant factor in experiment. Taguchi method is proven in various areas and the contribution is very huge in reducing the number of experiments (Taner and Antony, 2006; Yang and Tarng, 1998; Ghani et al., 2004; Nalbant et al., 2007; Lin and Lin, 2002).

2. Literature survey

WPT is widely used in many applications such as in medical and mobile technology (Odendaal and Li, 2005; Olvitz et al., 2012). Referring to the first pattern by Tesla (1900), electrical energy is transferred in high voltage up to megawatt power a several distance but the recorded information was unclear. The first transmission power had been done in 2007 with the transmission energy 7.5 times the radius of the receiver coil with 30% of real power at 10MHz frequency. Resonator with a quality factor 1000 can achieve 9 times of power transmission from the radius (Mur-Miranda et al., 2010). A few type of coil which is Radin coil, spiral and flat had been tested to identify the highest quality factor in design. The higher quality factor was claimed as a better resonator. Flat spiral coil is the highest with the transmission power of 26cm, 80% efficiency at quality factor 272.62. The result shows optimally designed system can increase the performance of WPT. For example, the same flat coil increased by 45.25% at a quality factor of 413.25 and 36.5% at the quality factor of 264.63 (Zambari et al., 2013). Quality factor including many apparatus such as number of turn in coil, diameter of coil, capacitor, inductor, resistance value and frequency. Eq. 1 shows on how to calculate the frequency. Quality factor can be calculated using Eqs. 2 and 3. ω = 2πf need to be substituted in Eq. 2. With a suitable circuit, quality factor can be determined.

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

It is difficult to get a device to identify electromagnetic field, but based on the frequency the performance of WPT can be identified. Many researches showed that better performance can be achieved with higher frequency. Most of the research shows the impact of the parameter. However, in the parameter, there is

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a better performance can be identified based on design algorithm. Algorithm design is based on the set of apparatus in the experimental design. Detailed research with the apparatus will increase the time and the cost to complete all experiments. These boundaries will create gaps in researches. Statistical analysis is important to identify the performance in any experiment. The purpose is to reduce the time and cost by reducing the number of experiments. For example, 4 parameters and 4 levels of experimental setup will require 256 numbers of experiments. The tool approach in this paper uses the Taguchi method. In a research by Asl et al. (2015), the result of hot pressing parameters and SiC content using Taguchi Methods, the best parameter produced about 96% of relative density and 15.2 Gpa for ZrB2-SiC composites. It had proved that Taguchi Methods give the best parameter selection in rooftop greening panel (Ushada et al., 2015). The result, then showed the photosynthesis rate, CO_2 absorption and L*a*b color with the quality robustness in rooftop building. Taguchi method proved that the result of the experiment shows L27 orthogonal array indicates that the fuel cell length plays important role in determine the fuel cell performance for current density and net power (Sasmito et al., 2015). This project will apply reducing number of experiments using statistical analysis, which is Taguchi method in WPT.

$$Q = \frac{\omega L}{R} \tag{2}$$

$$Q = \frac{2\pi f L}{R} \tag{3}$$

3. Development of wireless power transfer

WPT is a process of transferring electrical energy from one point to another point. Fig. 1 shows a block diagram of the system. The input voltage will be supplied to the inverter. The Inverter is a main part of the transmitter WPT system. Initially, the voltage inverter is a low voltage direct current (DC) type 12V to 36V that converts to alternating current (AC). The generated AC could be high voltage or low voltage depends on the input and component applied. Coil will be added in between the inverter circuit and converter circuit.

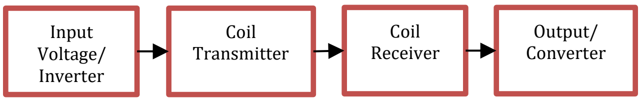

Fig. 1. Block diagram of the WPT system.

Fig. 2 shows the inverter circuit or known as transmitter circuit. The DC voltage was converted to AC Misplaced component can damage the circuit and power will not be delivered. L4 is a 200mH inductor with 1/4inch thirty (30) turns to increase magnetic efficiency.

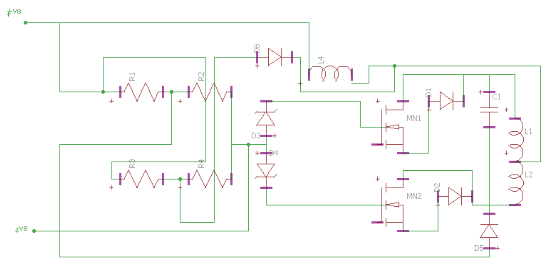

Fig. 2. Transmitter circuit.

Any turns for inductance can be applied to this circuit. R1 and R2 are the resistance for 470Ω 2W to reduce the present flow. Similar with R3 and R4 in which the resistance of 10k Ω is used to reduce the current flow. Zener diode indicated as D1 and D2. The aim of zener diode is to permit the voltage to flow in the circuit. To provide a low forward voltage with ultrafast recovery, ultrafast diode (D5 and D6) with 400V is used in this circuit. D3, QI and D4, Q2 indicated as a MOSFET IRFP250. AC capacitor self-addressed as C1. AC capacitor provides oppose changes in voltage by supplying current as charge or discharge in the circuit. L2 is set as a transmitter coil that received current and delivers it in an EMF wave. The EMF will produce a wave that able to be captured by the receiver circuit. Numerous coil sizes are often used such as 14, 24, 35 and 60 cm and therefore the larger the dimension of the coil, the often the power transmitted. Fig. 3 shows the inverter circuit that is used in low power experiment.

Fig. 3. Inverter circuit change form of DC to AC.

The aim of converter coil is to capture the EMF produced by inverter coil. However, AC capacitor and size of coil must be in the same size for both circuits. EMF flow within a coil and convert to AC type. When current flow inside the converter circuit, the current directly convert from AC to DC. Converter circuit is as illustrated in Fig. 4.

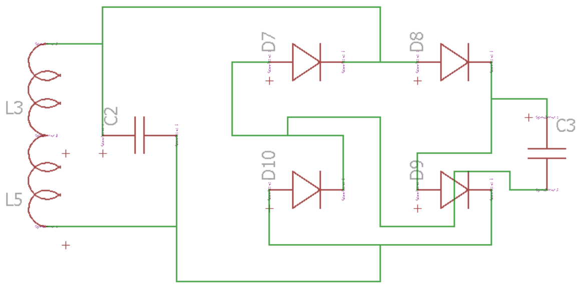

Fig. 4. Converter circuit.

The EMF produced an AC type of voltage through the coil. The AC voltage converted to DC type using a bridge rectifier and regulated based on the requirement from the load. Fig. 5 shows the circuit connected with 5V LED light.

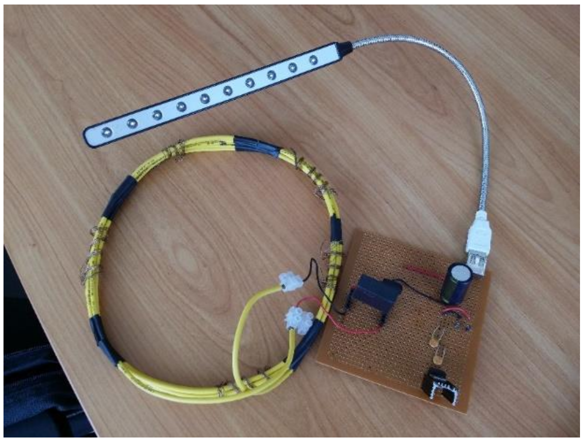

Fig. 5. Converter circuit with DC appliances.

A single coil in general consists of two basic elements which are inverter (Mohd et al., 2015) and converter. In order to capture a better EMF from the transmitter, coil and capacitor required to be in the same size. Fig. 6 shows the prototype of single coil WPT that has been used in this project.

Fig. 6. Single coil of WPT.

AC wave indicates voltage and current flows within the circuit in the form of AC. Monitoring on the signal wave; this circuit had been conducted using the oscilloscope. MOSFET characteristic is to fix the drain source and the waveform of this component as shown in Fig. 7. The peak to peak voltage is 41.2V. The current frequency is 49.97 Hz. During transmission, frequency of the coil will be different based on the capacitor and inductor inside the circuit. To get the most significant factor in the experiment, 4 parameters and 4 levels required 256 experiments. DOE is needed to reduce the cost and the time. However, many factors need to be considered to decide the significant parameter in WPT.

4. Results and discussion

This section will discuss on the methodology used to come out with the design of experiment using Taguchi method. All data are collected through the experiment based on the array orthogonal by Taguchi method. The main purpose of this research is to identify the most significant factor that reflects the WPT system.

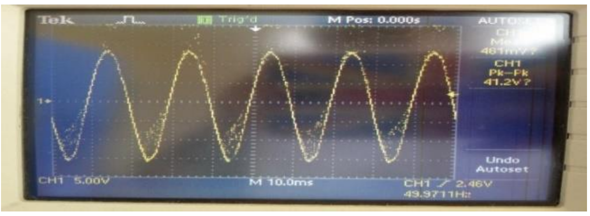

Fig. 7. Waveform on MOSFET.

A capacitor is a passive two terminal electrical component that has been used to store the energy for a temporary time in the electrical field. Capacitors are widely used as a storage device in an electrical circuit. 1.0μF, 2.2μF, 3.0μF and 4.0μF capacitors were used to carry out the experiment. Input voltage is a currency that is used in the experiment via the power supply. The current ranged between 8V to 14V. A complete transmitter and receiver circuit were arranged facing each other when the experiment is carried out. Each transmitter and receiver was connected with a copper coil. Transmitter and receiver were matched in a perpendicular axis of coil planes. C represents the current, r represents the radius of the wounded copper coil and d represents the distance as shown in Fig. 8. Once the setup has been made, two wires as an input (V) were connected to the power supply. The voltage that was applied is within the range of 8V until 14V. Then, 100μH-400μH inductor was connected followed by 1.0μF- 4.0μF capacitor. It was really important to make sure that the power of a capacitor in transmitter circuit was exactly the same with the receiver capacitor. A different in capacitor power will cause a failure in this experiment. Next, the positive wire was connected to the coil, while the other two wires were connected to the right and left of the copper coil. Fig. 9 shows a flow chart of the design of experiments. It started with material selection, parameter setting, construction of the circuit and testing. Taguchi method was used in Minitab software to identify a suitable algorithm to be used in this experiment based on the array orthogonal.

The experiment was reduced to 16 experiments instead of 256 experiments which is required for 4 parameters with 4 levels. Taguchi Methods is basically derived from matrices, so not all experiments will be included in the experimental design. In this research, the experiment was run using 4 factors and 4 levels. In this experiment, the parameters are as shown in Table 1, and number of experiments are shown in Table 2.

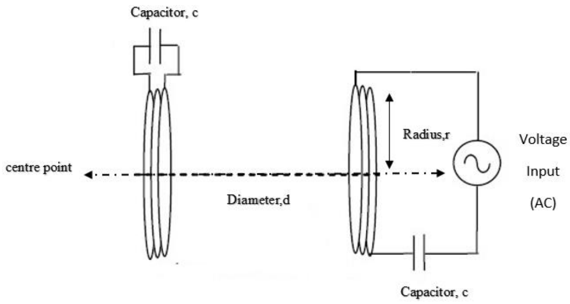

Fig. 8. The arrangement on the experiment.

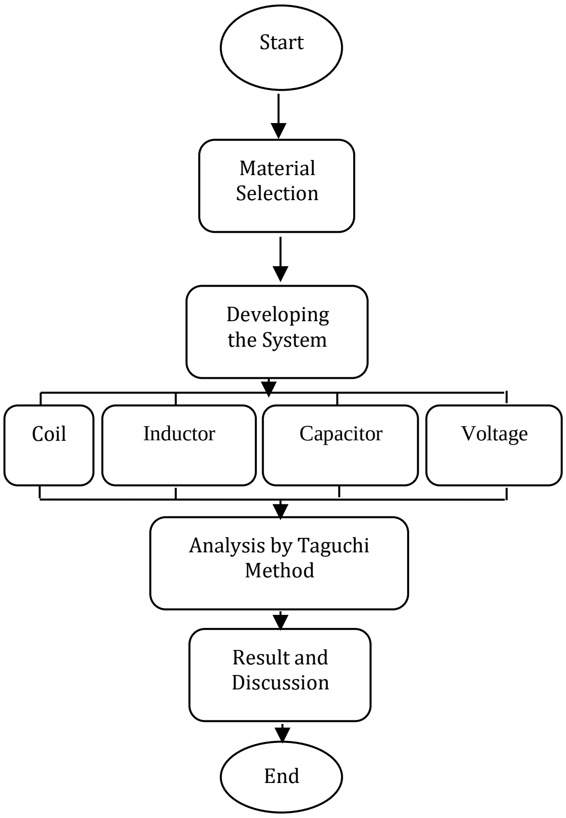

Fig. 9. The process flow on the experiment.

Table 1
Parameter and level setting.

Parameter/Level	Unit	1	2	3	4
Input	V	8	10	12	14
Size of Coil	Core	14	25	35	60
Inductor	μH	100	200	300	400
Capacitor	μF	1.0	2.2	3.0	4.0

Table 3 shows the result in range (cm) measured between the transmitter and receiver coil after achieving frequency. The S/N ratio is Signal Noise and this calculation involved a formula which is S/N = -10log10 (MSD). MSD represent Mean Standard Deviation (MSD) for every result in Experiment 1 and Experiment 2. The output is the voltage transferred after the receiver achieved the power from the transmitter. Eq. 4 shows the MSD.

$$MSD = (1/y1 + 1/y2)^2/2 \tag{4}$$

Table 2
The array orthogonal table.

Parameter/ No. of Experiment	A (Input)	B (Inductor)	C (Capacitor)	D (Coil)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	2	1	2	3
6	2	2	1	4
7	2	3	4	1
8	2	4	3	2
9	3	1	3	4
10	3	2	4	3
11	3	3	1	2
12	3	4	2	1
13	4	1	4	2
14	4	2	3	1
15	4	3	2	4
16	4	4	1	3

Table 3
Result of experiment.

Parameter No. of Experiment	A	B	C	D	Exp.1	Exp.2	S/N
1	1	1	1	1	13.5	13.9	22.73
2	1	2	2	2	14.5	14.1	23.10
3	1	3	3	3	15.0	16.0	23.79
4	1	4	4	4	17.6	18	25.01
5	2	1	2	3	18.2	18	25.15
6	2	2	1	4	27.2	26.4	28.56
7	2	3	4	1	14.5	14.3	23.17
8	2	4	3	2	17.6	17.2	24.81
9	3	1	3	4	21.6	21	26.57
10	3	2	4	3	18.3	18.9	25.39
11	3	3	1	2	20.5	20.1	26.15
12	3	4	2	1	18.5	18.1	25.25
13	4	1	4	2	17.0	16.6	24.50
14	4	2	3	1	19.5	19.3	25.76
15	4	3	2	3	22.0	23	27.04
16	4	4	1	4	30.0	29	29.39

Based on the main effect plot for mean that have been analyzed as shown in Fig. 10, the highest range in transferring the electricity was approximately 30cm. This was seen in experiment with input 14V, inductor 400uH, capacitor 1.0uF and 60 cm of cooper coil.

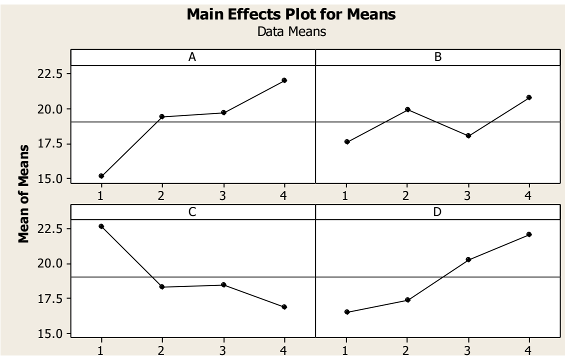

Fig. 10. Main effect plot for means.

The p-value is 0.100 which is bigger than 0.05, which mean the data is not significant as shown in Fig. 11. There is no significant difference between the actual data and ideal data. The data are normal.

Table 4 shows the average effect of each factor. Based on Table 3, level and parameter from S/N is analyzed. Every each level is categorized based on the type of parameter.

The total of S/N ratio from level 1 until level 4 is summed with different parameter. The total S/N ratio for different category in each parameter is call main effect. The total of main effect is divided with a total number of experiments as shown below.

$$\bar{T} = \frac{(22.73 + 23.10 + 23.79 + 25.01 + 25.15 + 28.56 + 23.17 + 24.81 + 26.57 + 25.39 + 26.16 + 25.25 + 24.50 + 25.76 + 27.04 + 29.39)}{16}$$

$$= 25.40$$

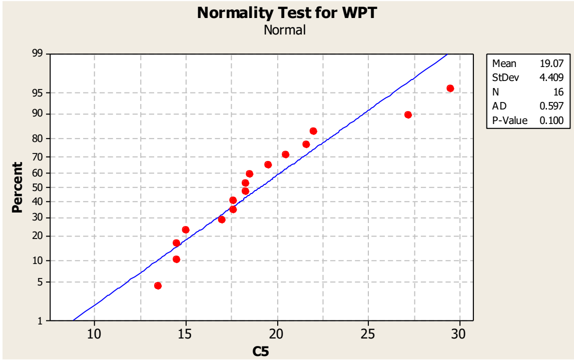

Fig. 11. Normality test for wireless power transfer experiments.

Table 4
Average effect of each factor.

Factor	Level	Total S/N Ratio (Level in parameter)	Main Effect
A	1	94.63	23.66
	2	101.69	25.42
	3	103.36	25.84
	4	106.69	26.67
B	1	98.95	24.74
	2	102.81	25.70
	3	100.15	25.04
	4	104.46	26.12
C	1	106.83	26.71
	2	100.54	25.14
	3	100.93	25.23
	4	98.07	24.52
D	1	96.91	24.23
	2	98.56	24.64
	3	103.72	25.93
	4	107.18	26.80
		Total	406.39

Table 5 shows the factor contribution in the experiment. The highest value was contributed from main effect in each parameter were deducted with the value of average effect (25.4). The value contributed was decided from the analyses result in Fig. 10 and Table 3.

Table 5
Factor contribution to the experiment.

Factor	The Highest Value Contribute	Factor Contribution
A	26.67	1.27
B	24.74	-0.36
C	26.71	1.31
D	26.8	1.4

Based on the highest result in main factor for each factor, the highest result for a parameter are A4B4C1D4. The expected is 30.1cm as shown below;

$$Y_{opt} = \bar{T} + (\bar{A}_4 - \bar{T}) + (\bar{B}_4 - \bar{T}) + (\bar{C}_1 - \bar{T}) + (\bar{D}_4 - \bar{T}) = 25.40 + (26.67 - 25.40) + (26.12 - 25.40) + (26.71 - 25.40) + (26.80 - 25.40)$$

$$= 30.1$$

Even though the algorithm based on the highest main factor is same with the highest result in an experiment, certain condition needs to be considered. The difference is less than 1% and the expected should be considered to reduce boundaries or obstacle. However, to confirm the most significant factor, analysis based on variant mean was conducted as shown in Table 6.

Based on this result on analysis of variance for mean as shown in Fig. 6, it shows that the most significant factor from this experiment is Factor A, Factor C and Factor D. This is because the value of Factor A, C and D were larger than 0.05. If the p-Value was larger than 0.05, it means that the factor we are using is not significant to the experiment that had been conducted. From this data, the percentage influenced is calculated. The value which is less than 10% was excluded from the second Analysis of Variance for Means as shown in Table 7.

Table 6
Analysis of variance for means 1.

Source	DF	Seq SS	Percentage Influence
A	3	97.96	33.6
B	3	27.79	9.5
C	3	75.58	25.9
D	3	80.11	27.5
Residual Error	3	10.14	
Total	15	291.57	

Table 7
Analysis of variance for means 2.

Source	DF	Seq SS	Percentage Influence
A	3	97.96	33.59
C	3	75.58	25.92
D	3	80.11	27.47
Residual Error	3	37.93	
Total	15	291.57	

Based on the previous Analysis of Variance for Means as shown in Fig. 7, it shows the Factor B was not significant to the experiment that has been conducted because its p-value was larger than 0.05 with 9.5% influence. Pure Sum indicates that the Factor D which represents the size of the coil has the largest value and this factor was the most significant factor in this experiment. From Fig. 12, it shows that the result distance versus signal noise (S/N) produced the highest distance achieved was 29.5cm with the algorithm A4B4C1D4. It followed by algorithm A2B2C1D4 (28.56cm), A4B3C2D3 (27.04cm) and A3B1C3D4 (26.57cm). As a result, factor D, C and A produced higher result with the value of 1.4, 1.31 and 1.27 respectively. Based on the algorithm result, factor C shows the minimum mean value of capacitor needed to produce the highest distance of power transmission. Factor B shows the lowest contribution with -0.36 and the effect on the algorithm was not significant. Although the value B is low in factor contribution in this experiment, but it contributes to achieve high frequency in order to get long distance of power (Dahalan et al., 2016) transmission.

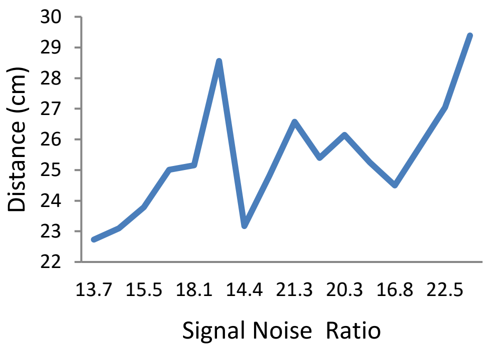

Fig. 12. Graph distance versus S/N ratio.

5. Conclusion

In conclusion, analysis of the result shows that the most significant factor in this experiment is Factor D, C, and A. Factor D and A is the most needed as compared to Factor C and B. The significant factor might be changed and depending on many factor related in the setting of parameter in the experiment.

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