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Autonomous Rail Rapid Transit (ART) Prototype Concept Using Wireless Charging System with Electromagnetic Induction Coupling

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ABSTRACT

The development of charging technology in Autonomous Rapit Rail Transit (ART) vehicles uses a wireless power system by optimizing. The selection of the power transfer method uses an Inductive coupling of the LCCL model with a wide variation in the cross-section of the wire and the diameter of the fixed coil. Scenario testing by installing a power transfer system on ART facilities, testing is carried out on coil inductance, resonance coupling gap and power efficiency. Optimum power transfer is obtained on coils with a cross-sectional area of 1.5 mm / 6.13 µH and the highest power transfer efficiency of 40% at a distance of 0.5cm.

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1. INTRODUCTION

In recent years, with the increase in automobiles, traffic congestion in urban areas has become more serious [1]. Redistributing urban road resources and building a diverse and modern urban public transport system is an effective solution to the current traffic congestion problem [2].The development of technology gave rise to the concept of autonomous vehicles to reduce transportation costs, energy consumption, pollution, break to reduce transportation costs, energy consumption, pollution, break down congestion, and improve transportation accessibility. These autonomous vehicles can reduce transportation costs for low-income communities and people with mobility problems [3]. In addition, Autonomous Vehicles are expected to provide benefits for traffic efficiency, safety, and energy savings[4].

Railway technology creates Autonomous Rail Rapid Transit (ART) without rails but rather highways equipped with white lines that are directly connected to the sensors on the train. ART is a new ground public transportation that offers punctuality, high capacity, energy efficiency, flexibility in operation, and low total costs [5]. ART was predicted to be the public transit trend in medium-sized cities [6][7]. The control of ART is mainly divided into two aspects, i.e., path tracking and longitudinal velocity planning and control[8].

ART is operated automatically without unmanned means for and without catenary electrical power supply sources. ART's energy source is lithium-ion rechargeable batteries that can be charged quickly [9]. Wireless power transfer uses capacitive couplings conductively by Sedehi [10] for deeply implanted biomedical devices (DIBDs). This method minimizes the patient's exposure to the heating of body tissues allowing the safe transfer of power into the body when using a minimum implant volume.

Design and construction of wireless power transfer (WPT) system using magnetic resonant coupling [11] for energy supply optimization. The efficiency improvement is significantly measurable according to the model theory, and the magnetic resonance coupling can be used to transmit power wirelessly from the source coil to the load coil. While the placement of the optimization source coil is adjacent to the load coil that is parallel to the capacitor on the terminal. Any change in distance and type of coil is known to affect the voltage capable of being transmitted.

Electromagnetically coupled resonators using toroidal ferrite core for Wireless Power Transfer [12], toroid coil type (T107/65/25-3F4) with outer diameter specification of 107 mm, inner diameter 65 mm, and height 25 mm. The frequency change between 0 - 1.5 MHz with a range of 500 kHz and the change in the distance between the two coils obtained an optimal frequency of 500 kHz with a magnitude of 8.3 at a distance of 3 cm. When the frequency is less than 500 kHz, the magnitude will be greater, while the magnitude will decrease. The difference in this study is in the type, dimensions of the coil, the frequency used, and the variation in distance between the two coils. Hybrid wireless power transfer (HPWT) systems combine inductive and capacitive coupling. The construction design places the capacitor clutch plate into one frame with the inductor clutch.

The concept of this electrical power distribution system requires a transmitter circuit as the transmitter and the receiver as the receiver. The transmitter consists of a series of high-frequency pulse direct current (DC) generating plants with an LC strand as a magnetic resonator. In contrast, the receiver consists of an LC strand with the same resonance frequency [13].

The most efficient coil can determine charging an electric vehicle (EV) via wireless power transmission (WPT). Power transmission determines EV position based on the sensor activated by the wheel. Charging optimization uses an individual coil power transmission efficiency measurement approach for use. Improved charging performance also minimizes energy loss by activating only coils with the highest transfer efficiency. The system can detect coils with maximum efficiency without using actual power transmission and measured efficiency comparisons. The receiver coil position charger setting can be detected energy saving and increasing charging time [14].

Various wireless power transfer studies were conducted to improve the relationship between distance and efficiency. Placement of coils to get maximum resonance, the efficiency of the power transfer system by arranging medium resonance coils. Models of helical coils and spiral coils with capacitors are considered resonance coils for WPT systems. Medium resonance coils are set perpendicular to Tx and Rx resonance coils sequentially to observe changes in efficiency according to direction. Power efficiency and matching Impedance conditions are calculated and intended using coupled-mode theory (CMT). The use of intermediate coils can increase efficiency and extend the distance between transmitter and receiver. Intermediate resonance systems have good efficiency and are superior to non-intermediate systems [15]. According to the book Wireless Power Transfer Principles and Engineering Explorations [16], wireless electromagnetic energy transfer resonance over medium distances, from fractions to multiple dimensions of resonators. With network theory, resonance inductive resonance links can be achieved very high efficiency, especially if the distance between the resonators is kept constant. With the appropriate design of the suitable network, the optimal connection can be established for the quality factor and the resonator connection. Regarding the wireless power transfer performed to increase efficiency by increasing longer distances in this paper optimized shunt-series resonance circuit structure.

Zhang et al [17] in their research consider electromagnetic or radio frequency (RF) WPT specifically. Because the RF signal is able to transmit information and power simultaneously. This paper specifically studies multiple-input multiple-output (MIMO) [18][19] wireless communication systems consisting of separate nodes, where one receiver harvests power while the other decodes information separately from a common transmitted signal to two receivers. Two different scenarios were also isolated, the first in which the second receiver and MIMO channels were different, and the other saw when they were placed together and saw the MIMO channels from the same transmitter.

From circuit analysis and numerical simulation, the advantages of shunt-series resonance coupling [20] have the advantage of high-efficiency transfer under different distances. A relative distance scaling factor is proposed to evaluate system performance, and optimization is defined as setting the ratio of transfer distance to resonance coil diameter. It was found that the transfer efficiency was close to expectations when it used shunt-series resonance with an optimized capacitor. This is especially useful if the clutch coefficient is very small, allowing for a longer transfer distance or a more receiving coil.

2. WIRELESS POWER TRANSFER

Wireless power transfer (WPT) is a great strategy for moving electrical energy from one point to another over a vacuum or atmosphere without the use of traditional cables or other materials [21]. WPT system is required to power electrical devices where physical interconnection of wires are impractical, dangerous or poorly arranged. WPT has inherent advantages such as enablement of transmission over long distances; convenient and flexible use; inexistent or low wear rates since use of wires have been greatly reduced [22]. WPT can be achieved using a number of methods including inductive coupling, microwave, and laser [23]. Research on WPT was conducted by Low et al [24], Lee at al [25], Kim et al[26], and Kurs et al[27]

Low at al focused on an approach proposed to achieve a very efficient WPT system that accomplishes a low-power loss by using the Class-E mode of operation. This system can accomplish an efficient power-delivery response over a range of load resistances with no control system or a feedback loop but depends on its natural impedance reaction or response to be able to accomplish its desired power-delivery profile over a wide range of load resistances, while maintaining a high efficiency to prevent any heating issues. Lee et al proposed an equivalent or a corresponding circuit model for the wireless transfer of power of 60W and above and examines the system based on the proposed model. The proposed model was validated using finite-element analysis (FEA) and some experimental results. Also, for high-power applications, there were investigations of the losses in WPT systems. Kim et al Kim et al, focused on the principles of magnetic field resonance WPT techniques while highlighting the effects of EM field noise from WPT and the related shielding methods for different applications. The efficient combination of this concepts helps ensure maximum power transfer. While, Kurs et al argued that there tends to be better efficiency of energy exchange with relatively little dissipated energy when two resonant objects of the same resonant frequency are coupled together.

WPT channels electrical energy from a voltage source to a load without wires. In energy distribution systems, the power delivered is very important so the efficiency of the link (η_{link}) needs to be considered [28]. Figure 2.1 shows the WPT system using an electromagnetic resonance coupling. Wireless Power Transfer [12]consists of a driver loop, transmitter coil (Tx), receiver coil (Rx) and load loop (load). Each antenna transmitter (Tx) consists of a loop and coil. When the generator powers the driver loop, the electric force of motion (electromotive force) induces the Tx coil. When the receiver coil (Rx) is excited (exited), the electric motion force induces in the load loop.

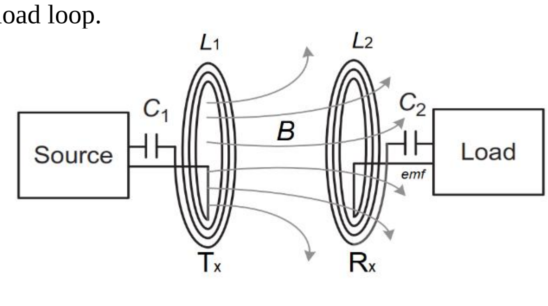


Figure 1. Concept wireless power transfer coupled LC resonant [10]

Interaction occurs because two coils have the same resonance frequency. The displacement current between the two coils due to the difference in potential of each cycle induces a magnetic field, resulting in a magnetic coupling between the two. This means coils of the same frequency can resonate, share electromagnetic fields, and channel energy efficiently. Power induction can be calculated using the following equation[29];

$$V_{ind} = -N\frac{d\emptyset}{dt} \quad (1)$$

$$\emptyset = B.A \quad (2)$$

Lorenzt Law = electromotive force (emf)
emf = $V_{exitasi}$

$$V_{ext} = -N\frac{d\emptyset}{dt} \quad (3)$$

Transformation of electrical power in the air, where the power moves, experiences a difference due to the electromagnetic receiver coil induction distance. While efficiency can be calculated from the power loss, where the difference between power transmitters and power receivers, so;

$$\eta_{link} = \frac{V_{ind}I_{ind}}{V_{ext}I_{ext}} \quad (4)$$

Where,

V_{ext} = Exitation voltage (Volt)
V_{ind} = Induction voltage (Volt)
I_{ext} = Exitation current (Ampers)
I_{ind} = Induction current (Ampers)
N = Turn coil value
B = Magnetic field (tesla)
A = cross section coil (m^2)
ϕ = Magnetic fluks (weber)

The resonance condition is that both coils have the same frequency (f). To analyze the frequency that can be generated from an LC circuit, the analogy that the inductive reactance value (X_L) is equal to the capacitive reactance (X_C) we can make it in the following equation:

$X_L = X_C$, if the reactance equation is reduced to $2\pi fL = \frac{1}{2\pi fC}$, next to be $f^2 = \frac{1}{2\pi 2\pi LC}$ and $f = \frac{\sqrt{1}}{\sqrt{2\pi 2\pi LC}}$, so it can be simplified to:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

Where,

XL = Inductive reactance
XC = Capacitive reactance
f = Resonant frequency
L = Inductance
C = Capacitance

The LC circuit forms alternating current from the direct current source. The characteristics of the inductor (L) are storing magnetic fields while capacitors (C) store electric fields [30]. The values L and C can affect the magnitude of the signal raised. The principle of filter C is filling and emptying the load. The filling lasts until the maximum value, when the voltage on C is equal to Vp. On the swing down, C will empty the discharged charge to L in the form of flux (□). If there is no load, the value is constant and equal to Vp, but if there is a load, then the output (Vout) ripples due to emptying conditions. The following equation following equation following equation can calculate the required value of C following equation can calculate the required value of C:

$$C = \frac{I.T}{V_r} \quad (6)$$

Where,

T = Wave period (s)
V_r = Ripple voltage (V)

The principle of electromagnetic induction is that when alternating current passes through a coil, around the coil will form a magnetic field (B). If, in this condition, is placed near the coil, then the first coil's magnetic field will also arise around the second coil. This is why cordless energy delivery can occur between the two coils. The value of L can be calculated using the following equation:

$$L = N\frac{\emptyset}{I} = N\frac{B.A}{I} = \frac{\mu_0.N.I}{l.I}$$

can be simplified to:

$$L = \mu_0 \frac{N^2.A}{l} \quad (7)$$

Where,

I = Current (A) μ_0 = Permeability ($4\pi10^{-7}$)

l = Coil long (m)

The resonance frequency of the coils is of the same value as the frequency of the alternating current, when the equivalent circuit of the coils is at a high frequency (f) and has the smallest impedance (Z). In these conditions these conditions and the most energy can be transmitted through the resonance.

3. RESEARCH METHOD

The system block diagram describes the application of the Autonomous Rapid Rail Transport facility, where when the means enter the stop, the inductive proximity sensor detects the means and then ignites the relay to channel the voltage from the 12V power supply to the transmitter circuit. Electrical power flows through the sending circuit to the resonant coil.

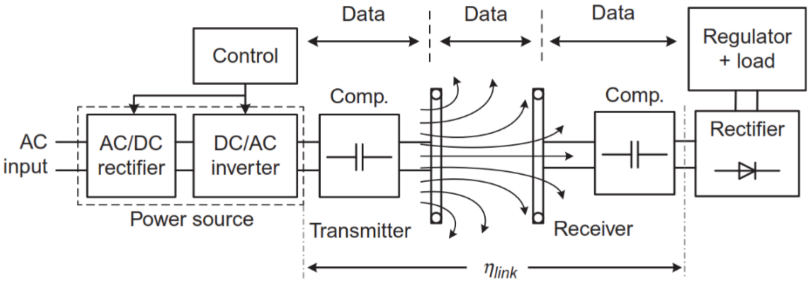


Figure 2. Block Diagram of Wireless Charging System

The resonant coil generates electromagnetic energy with a frequency equation with a frequency equation. The coil receives the energy radiated by the sending coil and then re-routed by the bridge diode. The output of the receiving circuit is divided into two regulators. 5Volt output as power supply equipment and 12Volt output pass-through current sensors and voltage sensors to know the magnitude of the current and output voltage of the receiving circuit as electrical power channeled to the load battery. Monitoring parameters using equipment devices.

Equipment is made using a MOSFETs that serves as a coil switch drive. This transmitter circuit works using a zero-voltage switching (ZVS) system. Electrical energy flows to the coil section quickly so that the coil produces electromagnetic which induces and causes Eddy Current. The transmitter circuit generates a magnetic field around the coil forming magnetic field lines. The magnetic field of this sending coil will induce a series of receivers on the condition that it must be in the area of the magnetic field force of the transmitter coil. The magnetic field generates a current in the receiving coil and is converted into a direct current in the receiver circuit using a diode. The current in this receiver circuit is raised using A1941 type transistors so that the output current from the regulator increases and can charge the batter.

The coil used is a solenoid in shape with a predetermined diameter and number of windings. This coil capture produces a magnetic flux in the sender's string. To captures produces a magnetic flux in the sender's string and captures electrical energy in the receiver circuit.

Figure 3. Transmitter and Receiver Coil Wireless Power System

$$N = \frac{B.l}{\mu_0.i} \quad (8)$$
$$= \frac{85\pi.10^{-6}.0,225}{4\pi.10^{-7}.3,2} = \frac{191,2}{12,8}$$
$= 14,9$ simplified to 15 turns

$$L_n = 2\pi.a.N \quad (9)$$
$$= 2\pi.3,25.15 = 306,15\ Cm$$

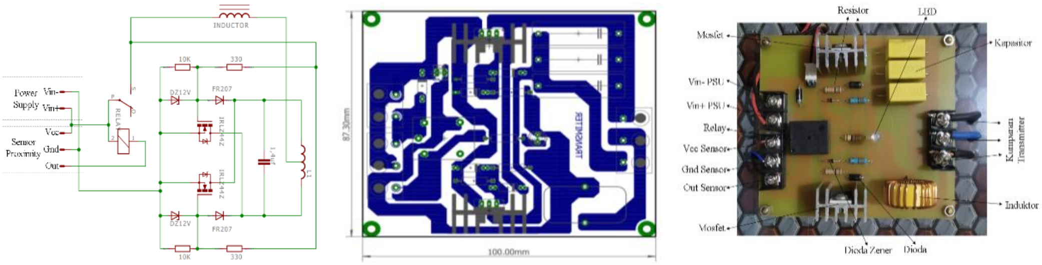
Where,

Ln	= Long wire	l	= Long solenoid
a	= Coil radius	μo	= Permeability magnetic
N	= Turn coil value	i	= Current
B	= Magnetic induction		

Prototype in the form of autonomous rail rapid transit (ART) uses fiber material with dimensions of 38 x 7 x 15cm. The inner prototype is used to put the equipment components used. The monitor is on the roof prototype. Prototype ART has a workflow starting from the means of entering the charging point until the monitor displays voltage and charging current. The ART design can be seen in the following image.

Figure 4. Prototype design autonomous rail rapid transit

Design transmitters use Schematic Diagram software Eagle. Several components include terminal blocks, relays, diodes, resistors, LEDs, MOSFETs, and capacitors. In the manufacture of this PCB using Eagle software. PCB itself functions as a link of electronic components in a computer with its conductor line layer. In this study, the type of PCB used is a single layer. Transmitter series combines several components into a circuit that serves as a sender of electrical energy to the receiver circuit wirelessly.

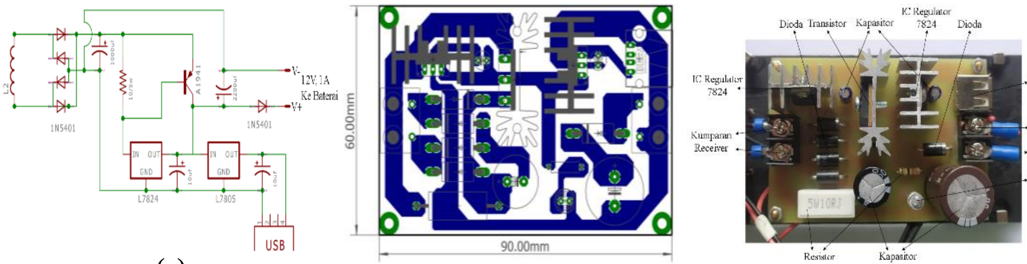


(a) (b) (c)

Figure 5. Transmitters wireless power system,

(a) Transmitter's schematic, (b) Transmitter's layout, (c) Transmitter kit

The design receiver also uses Schematic Diagram eagle software. There are components such as terminal blocks, diodes, capacitors, IC regulators, transistors, and USB ports. The receiver circuit is a combination of components that will react to the energy distribution of the transmitter circuit.



(a) (b) (c)

Figure 6. Receiver wireless power system,

(a) Receiver schematic, (b) Receiver layout, (c) Receiver kit

Coil testing using an L meter is a measuring instrument. The L meter indicates the inductance value on the transmitter coil and receiver coil inductance with the unit μH. The two ends of the coil are connected on pins L and G which are in the L meter. Then change the mode on the L meter of the period to measure the inductance value. Coils wrapped around by under the next calculation measured the inductance value. Schema Coil measurement can be shown in the following figure.

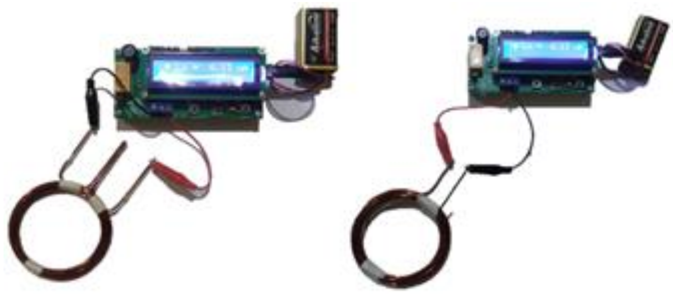


Figure 7. Coil testing schema

While the capacitance value is obtained from calculations using the formula C.

$$C = \frac{I.T}{Vr} = \frac{2{,}9.10^{-6}A \; x \; 1s}{2Vpp}$$

$C = 0{,}0000014F$ atau C = 1,4μF, So that the capacitance value of 1,4 μF.

Testing this transmitter by calculating the magnitude of the frequency that determines resonance. The calculation uses the inductance value and capacitance value entered in formula F.

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2x3{,}14\sqrt{6{,}13x10^{-6}.1{,}4x10^{-6}}}$$

$f = 18{,}39x10^{6}$Hz atau 18,3 MHz, So that the resonant frequency value is 18,3 MHz.

Test the receiver by bringing the transmitter coil and receiver coil closer together. In the event of electromagnetic wave resonance, the receiver circuit will receive power and the monitor can show the presence of voltage and flow of charging current to the battery on the receiver circuit.

Transmission gap testing is carried out to get parameter data which will then be used for wireless power system optimization. The test used a series of transmitters connected to a 12 Volt 5 Ampere power supply to generate electromagnetic induction on the transmitter coil. The transmitter coil and receiver coil are placed opposite each other. Next the gap between the coils from 0 cm to 4.5 cm with a step gap every 0.5 cm. Measurements are made to see the changes in energy that the receiver circuit can receive. To see the power that can be delivered, a digital multi meter is installed to measure the current and voltage. The digital multimeter is attached to the transmitter circuit input while the receiver circuit output is displayed on the monitor attached to the prototype.

Figure 8. Transmission gap testing

4. RESULTS AND DISCUSSION

4.1. Coil Testing

Coils are made using an enamel wire size of 1.0 mm wrapped around the shape of a circle with a circular diameter of 6.5 cm and as many as 15 windings. Make two coils that will be connected to the transmitter and receiver circuits and connected to the load in the form of a lithium-ion battery 18650.

Table 1. Enamel wire testing for 1,0 mm 7,26 μH

Gap (Cm)	Transmitter			Receiver			Efficiency (η)
	Voltage (V)	**Current** (A)	**Power** (Watt)	**Voltage** (V)	**Current** (A)	**Power** (Watt)	
0	12,5	3,0	37,5	12,8	0,9	11,52	30,72
0,5	12,5	2,3	28,75	11,6	0,6	6,96	24,2
1	12,5	2,2	27,5	9,2	0	0	0
1,5	12,5	2,2	27,5	7,8	0	0	0
2	12,6	2,2	27,72	5,9	0	0	0
2,5	12,6	2,2	27,72	4,3	0	0	0
3	12,6	2,2	27,72	3,1	0	0	0
3,5	12,6	2,2	27,72	1,3	0	0	0
4	12,6	1,4	17,5	0,1	0	0	0
4,5	12,6	1,4	17,5	0	0	0	0

The coil is made using a 1.5mm enamel wire wrapped around a circle with a circular diameter of 6.5 cm and as many as 15 windings. Make two coils that will each be connected to a series of transmitters and receivers and connected to the load in the form of a lithium-ion battery 18650.

Table 1. Enamel wire testing for 1,5 mm 6,13 μH

Gap (Cm)	Transmitter			Receiver			Efficiency (η)
	Voltage (V)	**Current** (A)	**Power** (Watt)	**Voltage** (V)	**Current** (A)	**Power** (Watt)	
0	12,5	3,2	40	13,1	1,2	15,72	39,3
0,5	12,5	2,5	31,25	12,5	1,0	12,5	40
1	12,6	2,3	28,98	11,7	0,3	3,51	12,11
1,5	12,6	2,2	27,72	8,5	0	0	0
2	12,6	2,2	27,72	6,0	0	0	0
2,5	12,6	2,2	27,72	4,6	0	0	0
3	12,6	2,2	27,72	3,4	0	0	0
3,5	12,6	2,2	27,72	2,4	0	0	0
4	12,6	2,2	27,72	1,2	0	0	0
4,5	12,6	2,2	27,72	0,3	0	0	0

4.2. Performance Wireless Power System

Transmitter performance is indicated by measuring the transmitting voltage, transmitting current, and transmitting power. The ratio of transmitter voltage in the coil whose cross-sectional area is 1.0 mm with the inductance of 7.26 µH and the voltage in the coil whose cross-section area is 1.5 mm with the inductance of 6.13 µH does not appear to change, the voltage is relatively stable, there is no voltage drop due to resonance load. The comparison of the transmitter current in the coil of 1.0 mm / 7.26 µH and the coil of 1.5 mm / 7.13 µH appears to change in current change current change due to the resonance load. The transmitting current in the 1.0 mm coil is first at a gap of 0 Cm large and stable at a gap of 0.5 – 3.5 Cm, but at a gap of 4 to above Cm it appears to drop. While the transmitting current in the 1.5 mm coil is first at a gap of 0 Cm large and stable at a gap of 0.5 - 4.5 Cm. Then the transmitting power occurs, the same thing with the transmitting current. The 1.5 mm/7.13 µH coil is more optimal in power transfer resonance, and the gap is further.

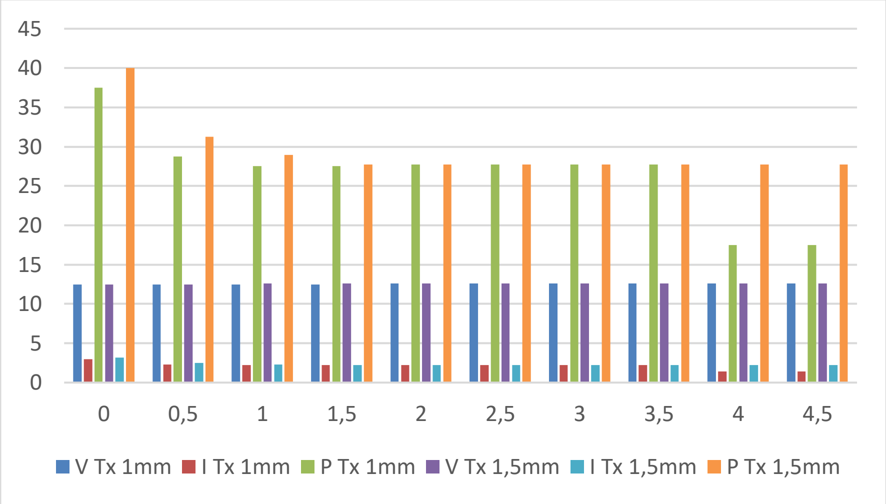


Figure 9. Comparison Graph of Transmitter Voltage, Current, and Power

Receiver performance is indicated by the measurable voltage received, receive current, and receiving power. The ratio of the receiver voltage in the coil whose cross-sectional area is 1.0 mm with the inductance of 7.26 µH and the voltage in the coil whose cross-section area is 1.5 mm with the inductance of 6.13 µH there seems to be a change, at first large but slightly smaller at a gap of 0 Cm and a voltage drop at a gap of 3.5 Cm in the coil of 1.0 mm. As for the 1.5 mm coil, the voltage is slightly greater at a gap of 0 Cm and can still resonate at a gap of 4.5 Cm. Voltage drop is caused by resonance load. The ratio received currently in the coil is 1.0 mm / 7.26 µH and the coil is 1.5 mm / 7.13 µH appears to have a change in current due to resonance load. The received current in the 1.0 mm coil can resonate at a 0 - 0.5 Cm gap. While the received current in the 1.5 mm coil can resonate at a gap of 0 - 1 Cm. Then with receiving power the same thing happens with the received current. The 1.5 mm/7.13 µH coil on the receiver circuit is also more optimal in power transfer resonance.

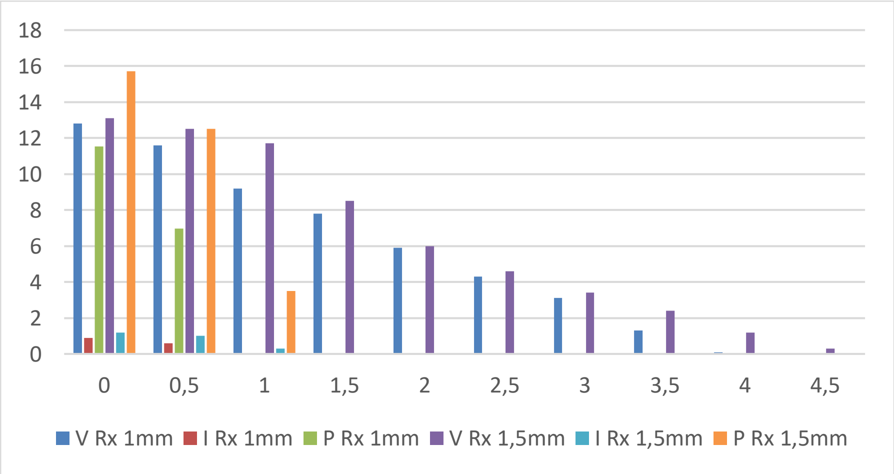


Figure 10. Comparison Graph of Receiver Voltage, Current, and Power

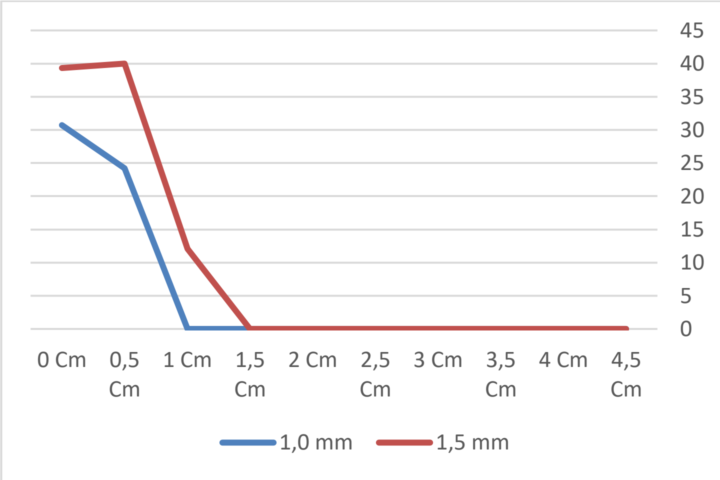


Figure 10. Efficiency Graph of Transmitter and Receiver

From the graph above, it can be explained that the use of coils with a wire size of 1.0 mm can get the highest efficiency of 30.72% at a distance of 0 cm (sticking to each other). While the use of coils with a wire size of 1.5 mm can get the highest efficiency of 40% at a distance of 0.5cm.

5. CONCLUSION

From the results of the wireless power system application research in the Autonomous Rail Rapid Transit (ART) prototype with Electromagnetic Induction, it can be concluded that the design of wireless charging in the Autonomous Rail Rapid Transit (ART) Prototype with electromagnetic induction produced by the transmitter circuit and receiver circuit and using coils of enamel wire measuring 1.0 mm and 1.5 mm wrapped around into a circle with a diameter of 6.5 cm as much as 15 windings. Based on the results of testing the transmitter and receiver circuit on the wireless power system prototype autonomous rail rapid transit (ART), the receiver coil that best receives electrical power is a coil with a wire size of 1.5 mm that can receive a voltage of 13.1 Volts and a current of 1.2 Amperes at a distance of 0 cm. The farthest distance in this test is 4.5 cm with a transmitter voltage of 12.6 Volts, the receiver coil with a size of 1.5 mm can still receive a voltage of 0.3 Volts at that distance. Better power transfer efficiency on 1.5 Cm coils can get the highest efficiency of 40% at a distance of 0.5cm.

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REFERENCES

[1] M. Saberi *et al.*, “A simple contagion process describes spreading of traffic jams in urban networks,” *Nat. Commun.*, vol. 11, no. 1, pp. 1–9, 2020, doi: 10.1038/s41467-020-15353-2.

[2] M. R. Jabbarpour, H. Zarrabi, R. H. Khokhar, S. Shamshirband, and K.-K. R. Choo, “Applications of Computational Intelligence in Vehicle Traffic Congestion Problem: A Survey,” *Soft Comput.*, vol. 22, no. 7, pp. 2299–2320, Apr. 2018.

[3] S. A. Bagloee, M. Tavana, M. Asadi, and T. Oliver, “Autonomous vehicles: challenges, opportunities, and future implications for transportation policies,” *J. Mod. Transp.*, vol. 24, no. 4, pp. 284–303, 2016, doi: 10.1007/s40534-016-0117-3.

[4] S. He, F. Ding, C. Lu, and Y. Qi, “Impact of connected and autonomous vehicle dedicated lane on the freeway traffic efficiency,” *Eur. Transp. Res. Rev.*, vol. 14, no. 1, 2022, doi: 10.1186/s12544-022-00535-4.

[5] D. Han, J. Wang, Y. Yan, M. Wu, Z. Lin, and Y. Guodong, "Velocity planning of the autonomous rail rapid transit with consideration of obstacles," *2020 4th CAA Int. Conf. Veh. Control Intell. CVCI 2020*, no. Cvci, pp. 35–40, 2020, doi: 10.1109/CVCI51460.2020.9338562.

[6] R. Huang, X. Yuan, Y. Hu, X. Zhang, X. Li, and X. Li, "Modeling and Simulation of All-Wheel Steered Multiple-Articulated Rubber-Tire Transit for Autonomous Driving Control," in *2019 IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2019, pp. 1–6. doi: 10.1109/VPPC46532.2019.8952378.

[7] X. Yang, X. Li, B. Ning, and T. Tang, "A survey on energy-efficient train operation for urban rail transit," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 1, pp. 2–13, 2016, doi: 10.1109/TITS.2015.2447507.

[8] A. Sorniotti, P. Barber, and S. De Pinto, "Path Tracking for Automated Driving: A Tutorial on Control System Formulations and Ongoing Research BT - Automated Driving: Safer and More Efficient Future Driving," D. Watzenig and M. Horn, Eds. Cham: Springer International Publishing, 2017, pp. 71–140. doi: 10.1007/978-3-319-31895-0_5.

[9] N. Ghaviha, M. Bohlin, C. Holmberg, and E. Dahlquist, "Speed profile optimization of catenary-free electric trains with lithium-ion batteries," *J. Mod. Transp.*, vol. 27, no. 3, pp. 153–168, 2019, doi: 10.1007/s40534-018-0181-y.

[10] R. Sedehi *et al.*, "A Wireless Power Method for Deeply Implanted Biomedical Devices via Capacitively Coupled Conductive Power Transfer," *IEEE Trans. Power Electron.*, vol. 36, no. 2, pp. 1870–1882, 2021, doi: 10.1109/TPEL.2020.3009048.

[11] S. Khalid Rahman, "Design and Construction of Wireless Power Transfer System Using Magnetic Resonant Coupling," *Am. J. Electromagn. Appl.*, vol. 2, no. 2, p. 11, 2014, doi: 10.11648/j.ajea.20140202.11.

[12] H. J. Lee, J. Y. Bang, and C. W. Chung, "Electromagnetically coupled resonators using toroidal ferrite core for wireless power transfer," *2012 IEEE MTT-S Int. Microw. Work. Ser. Innov. Wirel. Power Transm. Technol. Syst. Appl. IMWS-IWPT 2012 - Proc.*, pp. 183–186, 2012, doi: 10.1109/IMWS.2012.6215782.

[13] X. Gao *et al.*, "Design and Analysis of a New Hybrid Wireless Power Transfer System with a Space-Saving Coupler Structure," *IEEE Trans. Power Electron.*, vol. 36, no. 5, pp. 5069–5081, 2021, doi: 10.1109/TPEL.2020.3027473.

[14] M. Rozman *et al.*, "Smart Wireless Power Transmission System for Autonomous EV Charging," *IEEE Access*, vol. 7, no. c, pp. 112240–112248, 2019, doi: 10.1109/ACCESS.2019.2912931.

[15] Z. Li, S. Huang, M. Yang, and X. Yuan, "Transfer efficiency analysis of magnetic resonance wireless power transfer with multiple intermediate resonant coils," *Diangong Jishu Xuebao/Transactions China Electrotech. Soc.*, vol. 28, no. SUPPL.2, pp. 35–42, 2013.

[16] Y. Park, J. Kim, and K.-H. Kim, "Magnetically Coupled Resonance Wireless Power Transfer (MR-WPT) with Multiple Self-Resonators," *Wirel. Power Transf. - Princ. Eng. Explor.*, 2012, doi: 10.5772/28387.

[17] R. Zhang and C. K. Ho, "MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer," *IEEE Trans. Wirel. Commun.*, vol. 12, no. 5, pp. 1989–2001, 2013, doi: 10.1109/TWC.2013.031813.120224.

[18] O. Obinna, O. Kennedy, O. Osemwegie, and N. Nsikan, "Comparative Analysis of Channel Estimation Techniques in SISO, MISO and MIMO Systems," *Int. J. Electron. Telecommun.*, vol. 63, no. 3, pp. 299–304, 2017, doi: 10.1515/eletel-2017-0040.

[19] O. Okoyeigbo, K. Okokpujie, E. Noma-Osaghae, C. U. Ndujiuba, O. Shobayo, and A. Jeremiah, "Comparative Study of MIMO-OFDM Channel Estimation in Wireless Systems," *Int. Rev. Model. Simulations (IREMOS); Vol 11, No 3*, 2018, [Online]. Available: https://www.praiseworthyprize.org/jsm/index.php?journal=iremos&amp

[20] L. Chen, S. Liu, Y. C. Zhou, and T. J. Cui, "An optimizable circuit structure for high-efficiency wireless power transfer," *IEEE Trans. Ind. Electron.*, vol. 60, no. 1, pp. 339–349, 2013, doi: 10.1109/TIE.2011.2179275.

[21] A. M. Jawad, R. Nordin, S. K. Gharghan, H. M. Jawad, and M. Ismail, "Opportunities and challenges for near-field wireless power transfer: A review," *Energies*, vol. 10, no. 7, pp. 1–28, 2017, doi: 10.3390/en10071022.

[22] J. Li, "Research progress of wireless power transmission technology and the related problems," *AIP Conf. Proc.*, vol. 1820, no. March 2017, pp. 1–5, 2017, doi: 10.1063/1.4977407.

[23] S. D. Rankhamb and A. P. Mane, "Review Paper on Wireless Power Transmission for Energy Harvesting System," *Int. J. Sci. Res.*, vol. 5, no. 5, pp. 181–186, 2016, doi: 10.21275/v5i5.nov163268.

[24] Z. N. Low, R. A. Chinga, R. Tseng, and J. Lin, "Design and Test of a High-Power High-Efficiency

Loosely Coupled Planar Wireless Power Transfer System," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1801–1812, 2009, doi: 10.1109/TIE.2008.2010110.

[25] S.-H. Lee and R. D. Lorenz, "Development and Validation of Model for 95%-Efficiency 220-W Wireless Power Transfer Over a 30-cm Air Gap," *IEEE Trans. Ind. Appl.*, vol. 47, no. 6, pp. 2495–2504, 2011, doi: 10.1109/TIA.2011.2168555.

[26] J. Kim *et al.*, "Coil Design and Shielding Methods for a Magnetic Resonant Wireless Power Transfer System," *Proc. IEEE*, vol. 101, no. 6, pp. 1332–1342, 2013, doi: 10.1109/JPROC.2013.2247551.

[27] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *Science (80-.).*, vol. 317, no. 5834, pp. 83–86, 2007, doi: 10.1126/science.1143254.

[28] X. Dai, J. Wu, J. Jiang, R. Gao, and U. K. Madawala, "An Energy Injection Method to Improve Power Transfer Capability of Bidirectional WPT System with Multiple Pickups," *IEEE Trans. Power Electron.*, vol. 36, no. 5, pp. 5095–5107, 2021, doi: 10.1109/TPEL.2020.3032676.

[29] M. E. Davison, "A Simple Proof that the Lorentz Force, Law Implied Faraday's Law of Induction, when B is Time Independent," *Am. J. Phys.*, vol. 41, no. 5, pp. 713–713, May 1973, doi: 10.1119/1.1987339.

[30] J. Feng, Q. Li, F. C. Lee, and M. Fu, "LCCL-LC Resonant Converter and Its Soft Switching Realization for Omnidirectional Wireless Power Transfer Systems," *IEEE Trans. Power Electron.*, vol. 36, no. 4, pp. 3828–3839, 2021, doi: 10.1109/TPEL.2020.3024757.