THE COPPERBELT UNIVERSITY

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL ENGINEERING

WIRELESSLY POWERED ELECTRIC TRAIN MODEL

STUDENT DETAILS

AZARIA JIMBO	19136869	EEE
KAMWENGO KALUVI MUSONDA	19138636	TELECOMS
MWANGANA KALALUKA MUMEKA	19136274	EEE
OCTEVIA MWANSA	19141777	EEE

SUPERVISOR: DR. MUSA NDIAYE

DECLARATION

We hereby declare that we carried out the work reported in this report in the Department of Electrical Engineering, Copperbelt University, under the supervision of Dr. Musa Ndiaye. We solemnly declare that to the best of our knowledge no part of this report has been submitted here or elsewhere in a previous application for award of a degree. All the sources of knowledge used have been duly acknowledged.

NAME OF STUDENTS	SIGNATURE
AZARIA JIMBO	…………………………
KAMWENGO KALUVI MUSONDA	…………………………
MWANGANA KALALUKA MUMEKA	…………………………
OCTEVIA MWANSA	…………………………

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS/ABBREVIATIONS

1. Direct Current (DC)
2. Alternating Current (AC)
3. Electromagnetic Waves (EMW)
4. Electromagnetic Interference (EMI)
5. Electromagnetic Induction (EMI)
6. Electromotive Force (EMF)
7. Wireless fidelity (Wi-Fi)
8. Internet of Things (IoT)
9. Hertz (Hz)
10. Kilo Hertz (kHz)
11. Mega Hertz (MHz)
12. Electric Vehicles (EVs)
13. Electric Traction (ET)
14. Wireless Power Transfer (WPT)
15. Microwave Power Transfer (MPT)
16. Laser Power Transfer (LPT)
17. Line of Sight (LOS)
18. Capacitive Power Transfer (CPT)
19. Inductive Power Transfer (IPT)
20. Magnetically Coupled Resonance Wireless Power Transfer (MCR WPT)
21. Inductive Coupled Wireless Power Transfer (ICWPT)
22. Wireless Power Transfer System (WPTS)
23. Dynamic Wireless Power Transfer (DWPT)
24. Far Field Wireless Power Transfer (FFWPT)
25. Near Field Wireless Power Transfer (NFWPT)
26. Radio Frequency (RF)
27. Transmitter (Tx)
28. Receiver (Rx)
29. Pulse Width Modulation (PWM)
30. Sinusoidal Pulse Width Modulation (SPWM)
31. High Frequency Inverter (HFI)
32. Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
33. Integrated Circuit (IC)
34. Integrated Development Environment (IDE)

ABSTRACT

In recent years, the topic on wireless power transfer has been the center of discussion in the world of technology due to its undisputable conveniences it comes with. One such area this technology promises advancing is in the delivery of power to electric train. Thus, this project proposes the powering of electric train via wireless power transfer. This is achieved through magnetically coupled resonance of transmitter and receiver systems. The transmitter is supplied with a high frequency signal to switch power MOSFETs arranged in an H-bridge configuration. This system consists of a series – series compensation network which is used to improve the transmitted power. In addition, an online application will be used to monitor the transmitted and received power, and the transmitter coil active. This application shall receive the data sent from an ESP32 microcontroller. The data is stored in a MySQL database and retrieved for monitoring.

KEYWORDS

Electric Train, Locomotive, Wireless Power Transfer, Resonance, Coupling.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

In the year 1804, the world's first steam train was constructed and thereafter it brought about an industrial revolution. With the increasing use of tunnels and quest to make the train technology more effective, efficient and reduce environmental pollution electric trains were innovated. The first known electric locomotive was developed in 1835 and was powered by galvanic cells which had limited power thereby preventing its general use. To overcome this limitation a third rail running along between tracks was used in the world's first electric passenger train and was supplied with direct current of about 150 volts and was developed by Siemens and Halske in 1879. In this system a contact roller was used to collect the electricity from the rail [1],[2].

In 1883 Austria Vienna the first regular service electric train powered by an overhead line developed by Magnus Volk was opened [3]. When overhead cables are used; a pantograph, trolley pole or bow collector is used to deliver power to the train, meanwhile the pantograph is commonly used. The pantograph is a mechanical mechanism which is in contact with overhead electrical cables used to deliver power to an electric train [4].

In recent years, wireless powering of electric vehicles in transit (Dynamic Wireless Power Transfer) has become a subject of major interest due to the advantages it comes with such as overcoming range limitation [5],[6]. The earlier methods of power delivery to the train have a number of demerits due to their mechanical nature which include safety risks which are a result of loosening between contacts which causes arcing. In addition, the mechanical systems used require constant maintenance which increases cost on locomotive companies. Therefore, this project shall develop and demonstrate a method of powering an electric train wirelessly.

1.2 PROBLEM STATEMENT

Current electric trains are powered through a pantograph which is a mechanical mechanism used to collect and deliver electricity to an electric train from overhead cables that run besides the rail track. Since this connection involves a mechanical system, it is prone to wear and tear, as well as electrical arcing when the contact between the overhead cables and the pantograph is loosened, hence unsafe for the passengers on the train. In addition, the overhead cables and the pantograph require proper and frequent maintenance which is costly. Thus, a wirelessly powered electric train system would not have these shortcomings due to not having mechanical contact as a means of power delivery.

1.3 AIM

To design and model a magnetically coupled resonance wireless power transfer system to deliver electric power to an electric train model and develop its monitoring system.

1.4 OBJECTIVES

- To design a magnetically coupled resonance wireless power transfer system.
- Fabricate the wireless power transfer system and install it on an electric train model.
- To develop an Internet of Things (IoT) Monitoring System which shall monitor the power transmitted and received.

1.5 JUSTIFICATION

According to report 06/2013: Accident involving a pantograph and the overhead line near little port published by the rail accident investigation branch on the 10th December 2014. Upon reaching the location of the accident with a speed of 129 km/h the pantograph lost contact with the overhead line due to long term movements of the line support mast and force of the wind at the time of the accident [7].

As earlier elaborated in the problem statement to alleviate such incidents as mentioned, frequent maintenance of the overhead lines supports and pantograph are required. This tends to be costly to the locomotive companies as they would be expected to change the overhead lines and have the pantograph replaced if any fault or failure occurs because these mechanical parts are prone to wear and tear and must be replaced frequently [8],[9],[10].

Therefore, this project is aimed at designing and developing a wireless power transfer system that will deliver power to an electric train wirelessly. This would alleviate incidents such as the above mentioned as well as reduce maintenance costs as the power delivery system will not depend on any moving parts.

1.6 PROJECT SCOPE

This project will include:

- A review of previous and current methods used to deliver power to electric trains.
- Proposal of a system that will deliver power to an electric train though resonance inductive coupled wireless power transfer.
- Design and fabricate a scaled down prototype to validate the proposed system.

This project will not include:

- Designing and fabrication of a model train to be used.
- Dedicated study and proposal of electromagnetic interference and shielding.
- Fabrication of a direct current power supply.
- Design and fabrication of a battery charge control.

1.7 METHODOLOGY

The proposed system can be divided into three main units. These units comprise; unit one (U1) the transmitting system, unit two (U2) the receiving system, and lastly unit three (U3) the Online Application for monitoring. Figure 1 shows a block diagram illustration.

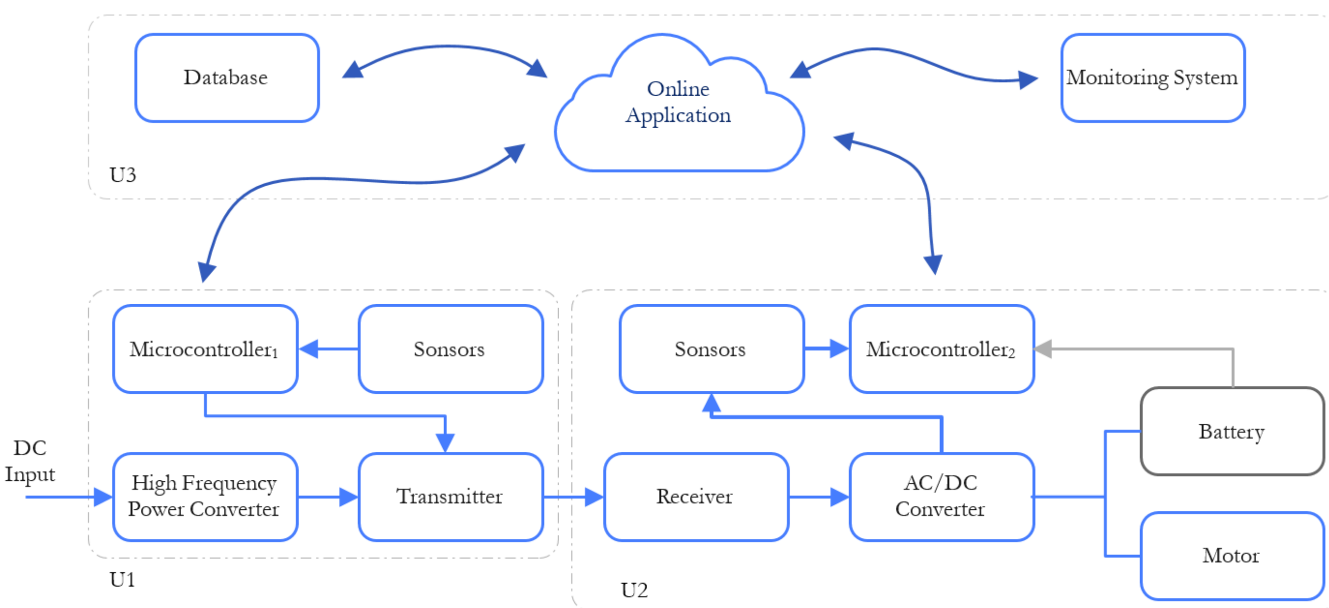


Figure 1: functional units block diagram

Unit One: In this unit, the input power is supplied (DC supply). A converter consisting of a pulse width modulation inverter IC SG3525 is used generate a high frequency PWM signal at 80 kHz which is fed to the MOSFET driver IC, this driver IC is then used to driver an H-Bridge made up of IRF540 power MOSFETs. The H-Bridge produces an alternating output which is then supplied to the transmitter/s. The transmitter is made in such a way that it is segmented and the transmitter coil that is turned on is dependent on the position of the train while the rest remain off. This is achieved by using sensors to determine the position of the train and send an appropriate signal to the ESP32 Microcontroller which then switches on or off the transmitter coils through the use of relays. In order to increase transmission efficiency, a resonance inductive coupling approach is used. Here the coil inductance is made to resonate with a series capacitance thereby eliminating the reactive power since the inductor and capacitor cancel out at resonance.

The sensors in unit one includes; sensors used to determine the location of the train, voltage sensor made up of a resistor voltage divider, and the current sensor ACS712 which is used to determine the current drawn (the values of voltage and current are used to determine the power). The values from these sensors are fed to the ESP32 which process the information and eventually sends them to the online application through Wi-Fi by the use of the ESP32.

Unit Two: This unit is the receiving end and it mainly comprises the receiver coil with a series compensation capacitor, an AC/DC converter, and the motor as the load. The transmitter coil creates a magnetic field which links with the receiver coils, as a result an alternating current is induced in the receiver coil. This is rectified by the AC to DC converter because the required voltage is DC since the motor on the train is a DC motor. The output of the converter is fed to the motor to drive the train. The battery is a backup source in case there is a system failure thus, it is not the main supply for the motor. A voltage and current sensor is used to measure the rectified voltage and current drawn by the load the results are fed into the ESP32 Microcontroller. Similarly, to the microcontroller in unit one the microcontroller in this unit is used to collect the sensor data, determine the power and send the data to the online application through Wi-Fi.

Unit Three: The monitoring system makes up the third unit, this is an online application that can be used to visualize the transmitted and received power, and the transmitter coil on at a particular time. This online application is a PHP based website, it shall receive the sent data and display the appropriate visuals on the monitoring system (front end). Any data needed to be stored shall be recorded in MySQL database. The data from the ESP32 Microcontrollers will be received on a PHP script, and the data to be visualized will be accessed via ajax, a JavaScript web development technique used to retrieve data from a server on another PHP script. Software's used packages used to develop the code include; visual studio code, XAMPP server.

Other software's used include the Arduino IDE used to develop the code for the microcontrollers, and proteus for the simulations. Simulations will only have components that have libraries in the software package or equivalent component will be used to simulate the intended result.

CHAPTER 2: LITERATURE REVIEW

2.1.0 THE ELECTRIC TRAIN

Earlier, locomotives were primarily powered using steam. As the manufacturing of electrical machinery improved, the various companies producing this machinery were looking for new fields to invest in. Not much interest from the railway administrators was allocated to these advancements. They actually faced a lot of hostility because their designs were not a match to those of the steam trains. Agreements with the railway administrations were only reached after continued struggles. Meanwhile, the electric locomotive was slowly replacing the steam locomotive on a small scale in several countries [11].

The adoption of electric powered locomotives was as a result of the steam locomotives that polluted underground subways and tunnels. The introduction of alternating current electric locomotives was brought about by the efficiency and simpler manufacturing which in turn made these locomotives feasible on stepper sections of track and longer lines.

2.1.1 TYPES OF ELECTRIC TRAINS

Electric trains are categorized into three types mainly Direct Current (DC), Alternating Current (AC) and Composite system. This classification results from the type of electricity supplied to the train. Power is delivered depending on the type of electric train either being direct current or alternating current [12].

Direct Current Trains

Power is supplied to the train in two different ways which are the third and overhead railway. When a third railway running along between tracks is used, collection of electricity is done using a contact roller on the train. It operates using low voltages ranging between 600V to 1200V.

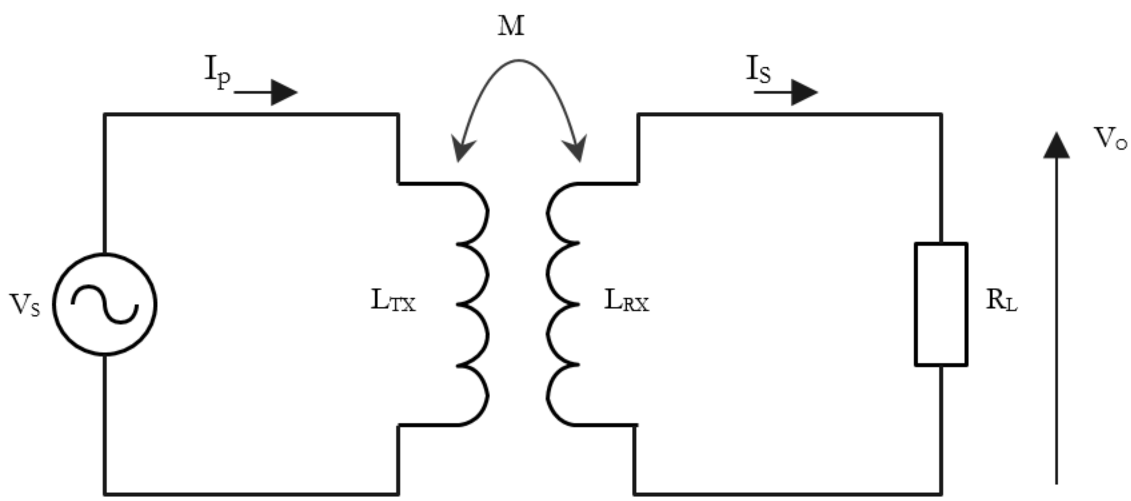
Alternating Current Trains

In alternating current trains, power is supplied to the train through a pantograph. The pantograph collects electricity from overhead cables running along the railway tracks. Typical voltages range between 11 $kV - 16\ kV$ while the frequencies range between 16.7 to 50 Hz.

2.2.0 WIRELESS POWER TRANSFER

Wireless power transfer is a way in which electricity is transmitted between none-electrically connected points [13]. Wireless power transfer undoubtedly brings about improvements in the reliability and convenience of application such as transportation. In addition, it provides a way of overcoming issues of range and electrical storage limitations faced in the electric vehicle transportation sector [14]. Although this technology had not seen much attention in its early days, it has greatly been an area of interest in recent years which has led to huge success though still in its early stages.

Basically, WPT operates like an air core transformer. The power is transmitted through either an alternating electric field or commonly through a magnetic field. Just like the transformer it consists of a primary and secondary coils, though being similar the distance between the primary and secondary in WPT leads to low coupling between the coils nevertheless, transmission of large amounts of power has been achieved due to improvements in the technologies [5]. The schematic in figure 2 below shows a basic WPT system.



Where,
Vs : Supply Voltage L_{TX}: Transmitter Coil Inductance
V_O: Output Voltage L_{RX}: Receiver Coil Inductance
Is : Secondary Current M : Mutual Inductance
I_P: Primary Current RL : Load

Figure 2: basic wireless power transfer system

2.2.1 REVIEW OF THE TYPES OF WIRELESS POWER TRANSFER

Transmission of power wirelessly can be classified depending on the distance through which the power can be transmitted, and the method used for the transmission. This is illustrated in the figure below.

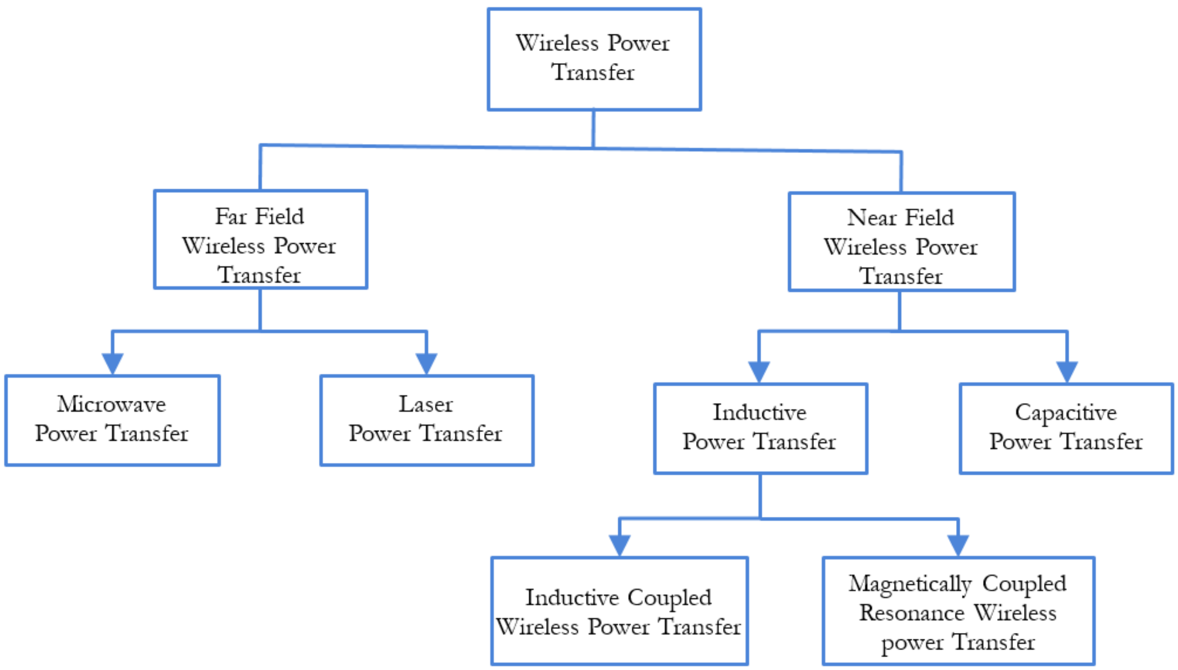


Figure 3: Types of wireless power transfer methods

As illustrated in figure 3 above, Wireless Power Transfer (WPT) aside being classified into Near Field and Far Field Wireless Power Transfer, it can further be divided based on the technology used.

Far Field Wireless Power Transfer (FFWPT)

Far-field wireless power transfer as the name suggests involves transfer of electricity over long distances through the use of electromagnetic waves for energy transfer. The energy is delivered in the form of radiation (the transferred energy is in the form of the electric field component of the electromagnetic wave) and thus, is also referred to as electromagnetic radiation wireless power transfer. This type of Wireless Power Transfer is divided into two types [13]: The first being Microwave Power Transfer (MPT) and Laser Power Transfer (LPT). It is worth noting that this type of wireless power transfer is dependent on line of sight (LOS).

Microwave Power Transfer (MPT): In this type of WPT microwave devices such as the magnetron are used for radiating a signal in the form of a radio wave by use of a suitable transmitter (Antenna). At the receiving end, an antenna is used to collect the radiated energy. Microwave power transfer is widely used when there is a need to supply devices located at long distances and unfavorable weather conditions. This technology requires the use of large transmitters resulting in it being expensive [15].

Laser Power Transfer (LPT): In this Technology, power is transmitted by use of highly concentrated laser light aiming directly at the receiver and as a result can achieve efficient power delivery across long distances. The receiver uses photovoltaic cells specialized for the particular use to convert the received light signal into electric power [16]. This laser radiation is hazardous due to high energy concentration. Since, LPT uses visible or near-infrared frequency the transmitted signal is vulnerable to atmospheric absorption. This method's actualization becomes expensive due to it requiring a large variety of devices and complicated tracing systems.

Near Field Wireless Power Transfer (NFWPT)

Near field wireless power transfer unlike far field WPT is non radiative and is based on the principle of coupling of the magnetic field between two coils. This shall occur in a distance through which the energy is transmitted. Since the magnetic field of an electromagnetic wave attenuates faster than the electric field, power transfer over a given distance is limited. In this method of transmission, the energy can either be transmitted through a magnetic or electric field and as a result, it can be classified into two namely: Capacitive Power Transfer (CPT) and Inductive Power Transfer (IPT) [17]. Capacitive Power Transfer utilizes an electric field while Inductive Power Transfer uses a magnetic field for wireless power transmission.

Capacitive Power Transfer (CPT): Capacitive power transfer utilizes capacitive coupling between the transmitter and the receiver. The transmitter and receiver are electrodes forming the capacitor in the form of metal plates. The transmitter is supplied with an alternating voltage, this oscillating electric field through electrostatic induction results in an alternating potential on the receiver plate due to induction, this into alternating current and flows to the load circuit. In capacitive power transfer, there must be a very short distance between the transmitter and receiver for effective transmission. This technology is cheaper than inductive power transfer, flexible and small in size making it suitable for medical implants [18]

Inductive Power Transfer (IPT): This is further delimitated into Magnetically Coupled Resonance Wireless Power Transfer (MCR WPT) and Inductive Coupled Wireless Power Transfer (ICWPT).

Inductive Coupled Wireless Power Transfer (ICWPT): This operates similarly to the operation of an air cored transformer. It is based on the transfer of power through a magnetic field which occurs when magnetic flux from a transmitter coil cuts the receiving coils while the two coils are magnetically coupled together [19]. The coupling between the coils decreases with increase in distance between the transmitter and receiver coils as a result the power delivered is reduced, the typical distance used ranges from a few millimeters to a few centimeters. This system operates in the kilohertz frequency range and allows for power transmission between a few watts to kilowatts depending on the effectiveness of the system.

Magnetically Coupled Resonance Wireless Power Transfer (MCR WPT): Similar to inductive coupled wireless power transfer, magnetically coupled resonance wireless power transfer operates on the principle governing the air cored transformer. However, the transmitter and receiver coils operate at the same resonance frequency [20]. Here the frequency ranges from a few kilohertz to megahertz. By use of this technology, it is possible to achieve up to fifty percent efficiency over a distance of several meters while unaffected by ambient conditions. Unlike far field wireless power transfer techniques, this does not depend on line of sight. Due to the non-radiative nature of magnetically coupled resonance wireless power transfer and it being more efficient than inductive coupled wireless power transfer it is the most efficient method for medium range wireless power transfer. Nevertheless, the increase in distance and axial mismatch between transmitter and receiver leads to decrease in efficiency of transmission.

COMPENSATION

In order to transfer power efficiently, the system is made to operate at resonance through compensation [19]. The compensation topologies basically consist of either a single capacitor in parallel or series to the transmitter and receiver coil inductors forming a resonant circuit. In the transmitting side, the compensation network is used to reduce the reactive power by canceling out the reactive component of the transmitter coil. While the compensation on the secondary side is used to nullify the receiver inductance thereby improving the power transfer capability of the system [17]. The compensation network on the transmitter side is connected between the high frequency inverter and the transmitter coil, while in the secondary it is connected between the receiver coil and the rectifier.

2.3.0 DYNAMIC WIRELESS POWER TRANSFER

2.3.1 REVIEW OF TESTED METHODS

The Korea Advanced Institution of Science and Technology (KAIST) and the Korea Railroad Research Institute (KRRI) have developed high capacity transportation systems such as railways that employed wireless power transfer technology.at a stable constant rate, the technology supplies 60 kHz and 180 kW of power remotely. A test was carried out successfully which was showcased to the public at Osong Station in Korea. The train was able to receive 20 kW and 100 kW power at 85% transmission efficiency rate while maintaining an air gap of 20 cm [6],[10].

The Japan Technical Research Institution proposed a design with long bipolar coils and the coils are used as the matching pickups. This system transfers 50 kW of power with an air gap of 7.5 mm [6].

Germany is currently leading in WPT technologies. Bombardier Primove has conducted studies for a better exploitation of the technology. Articles are yet to be published but a design was released which emphasizes on high reliability when powering the train.

2.3.2 POWER SUPPLY TOPOLOGIES

There are three main arrangements in which the power supply is connected to the transmitter/s. This is as a result of the need to overcome issues of low power transfer efficiency and high sensitivity to changing parameters. These topologies are; centralized power supply unsegmented rail topology, segmented rails and power supply mode, and centralized power supply and segmented rails [6],[19].

i) Centralized power supply unsegmented rail topology.

As the name suggests, this arrangement comprises a centralized power supply with an unsegmented rail thus, having fewer number of components but has high requirements since a single supply supporting large power compared to the other topologies. Nevertheless, the system is sensitive to variations of parameters due to increased length of the transmitter rail.

In this topology the entire rail is active resulting in undesirable high losses. Since the transmitter is not segmented it is unreliable as any breakdown affects the entire rail and has high self-inductance which would create high voltage spikes. In addition, this topology has low efficiency when the load is small.

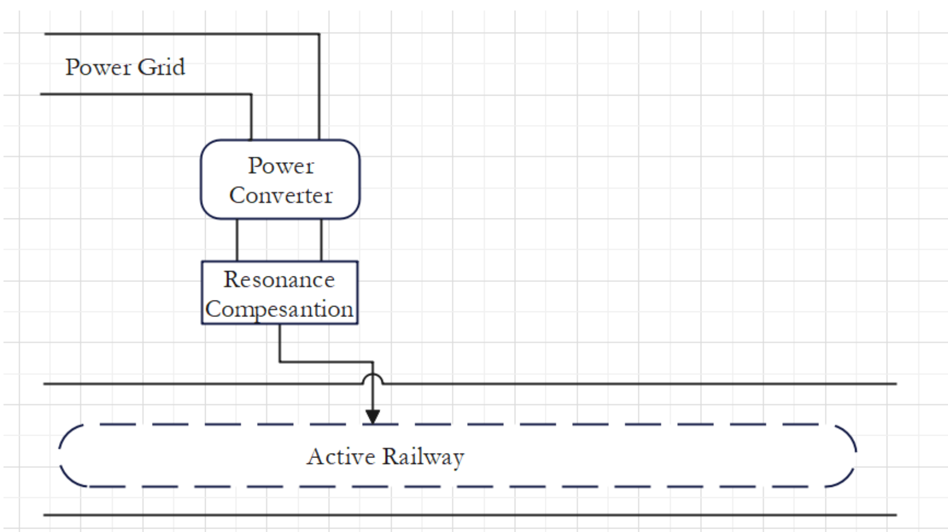


Figure 4: Centralized power supply unsegmented rail topology

ii) Segmented rails and power supply.

The segmented rail and power supply topology is such that each segment comprises its own power converter. The advantages of such a scheme include reduction of power loss since different segments can be switched on at different times. High reliability because each segment has its individual power converter operation in other segments continues normally even when another segment has a fault. The power converters are smaller-sized. This topology ensures a stable system as it is less sensitive to variations and lower self-inductance.

The drawbacks of this topology include; high number of converters, which results in high maintenance and construction cost. Since there are a high number of converters they are difficult to control. To implement this topology a high number of components are required thus making the system have a low reliability as a whole.

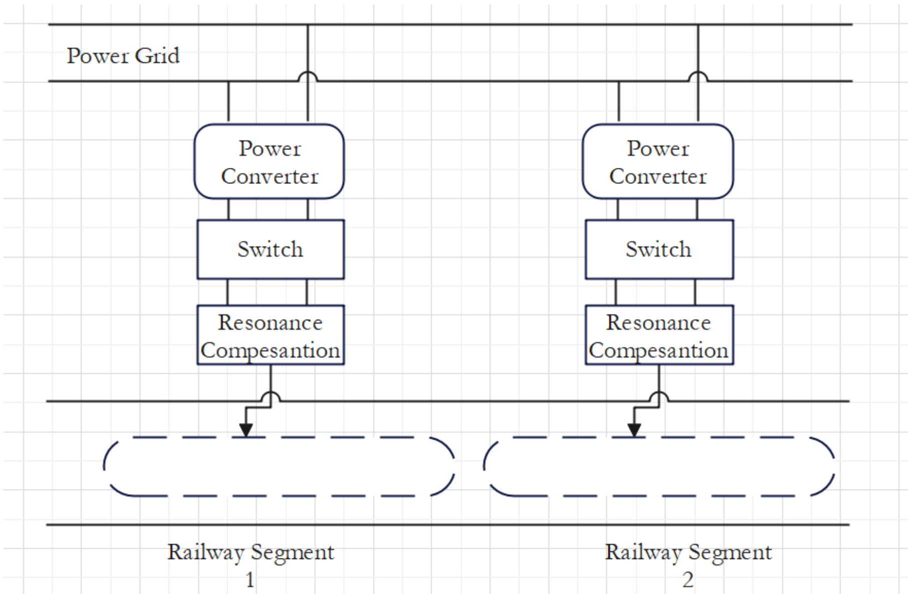


Figure 5: Segmented rails and power supply

iii) Centralized power supply and segmented rails.

In this topology the power supply is centralized thereby lessening the number of power converter units required which also makes it easier to maintain. In addition, there is lower self-inductance and is less sensitive to variations. Not only does this topology allow for different segments to be activated at varied periods thus, reducing power loss but also increases stability.

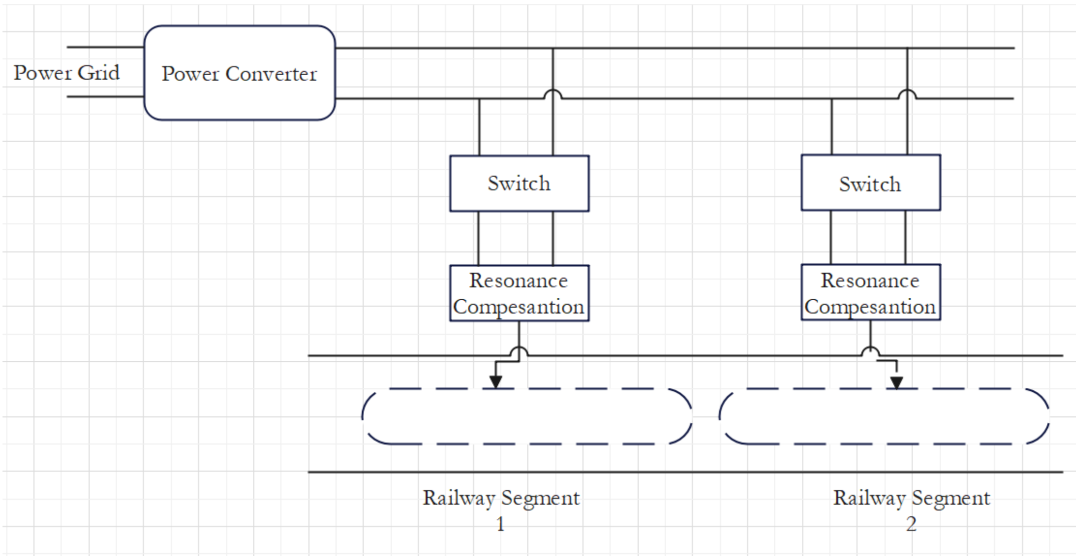


Figure 6: Centralized power supply and segmented rails

2.3.3 HIGH FREQUENCY INVERTER

Power supplied at the transmitting side of the system is either direct current (DC) or alternating current (AC) of low frequency, in either case the supplied voltage frequency must be increased to effectively link the transmitting and receiving coils for useful power transfer [21]. This operating frequency is determined by the resonance frequency of the coils and compensation network, and ranges from 20 kHz to 100 kHz. This will be the switching frequency of the inverter. In the case of alternating current supply, the AC is first converted into DC by use of rectifiers then converted to high frequency AC. This is known as two stage conversion. When the supplied power is DC, single stage conversion is applied. The DC is converted to high frequency AC directly. The converter responsible for this is referred to as a high frequency inverter. It takes the DC input and converts it to high frequency AC which is used to power the primary transmitting coils.

Once the secondary coils receive the power from the transmitter, it is fed into the rectifier which converts it back into DC and then filtered. This can then be used directly or converted back into AC of appropriate frequency which can be used to operate equipment. For the maximum power to be transmitted, the load impedance must match that of the source according to the principle of maximum power transfer [5],[22].

Since these converters operate at high frequencies they are prone to high switching losses since losses increase with increase in frequency. In addition, skin and proximity effects occur which reduce efficiency. To avoid this, the technique called zero voltage switching is employed. This is done in such a way that switching only occurs between on and off states (this is also true for zero voltage switching) [23].

Power Inverters are commonly made of power semiconductors such as the insulated bipolar transistor (IGBTs) or metal-oxide-semiconductor field effect transistors (MOSFETs). These act as switches and are connected in a parallel fashion forming a half bridge or a full bridge (H-bridge converter) when high power output is required [24].

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