Improved Hybrid Bus for OC Transpo: Report of Findings

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Date: Friday, December 6th, 2019

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EXECUTIVE SUMMARY

A diesel hybrid bus uses 30% less fuel than a diesel bus, which reduces greenhouse gas emissions by 30 tons of carbon dioxide per year. A diesel hybrid bus uses electric power and diesel engine to move the bus. Combining both of these technologies allows less fuel consumption, and hence reducing the emissions of greenhouse gases.

An ultracapacitor could be used together with lithium ion batteries to improve the energy source for a new improved hybrid bus. Batteries can be charging and discharging. When batteries are discharging it is giving its energy to other components of the hybrid bus during the redox reactions (reactions where energy is being released and absorbed by other chemicals). All energy conversions can be explained using the first law of thermodynamics. Energy management can be improved by using ultracapacitors. Overall, this reduces costs on maintenance, fuel and store more energy.

An Electric motor is used in a hybrid bus to provide acceleration. Electric motors reduce the fuel-consumption and the Carbon dioxide emissions when compared to a conventional diesel-engine bus. A Chorus Meshcon multi-phase motor can generate more 'burst' and start-up torque than motors used in existing OC Transpo hybrid buses. Therefore, Chorus Meshcon is selected to be implemented as the electric motor for the hybrid bus.

1.0 INTRODUCTION

This document is a report of findings written for Mr. Manconi, as part of a team project in the CU Engineering class. The purpose of this report is to suggest new technologies that will solve the problems regarding high maintenance costs and short battery life that caused OC Transpo to stop using their previous hybrid buses. This report is divided into three sections relating to how OC Transpo can improve their hybrid buses: Improved Hybrid Bus Overview (Section 2), Diesel Engine (Section 3), Batteries (Section 4), and Electric Motor (Section 5). Glossary terms are shown in italic format throughout the report.

2.0 IMROVED HYBRID BUS OVERVIEW

OC Transpo is getting rid of the hybrid buses, as they are not cost effective [1]. So, this research is aims to improve parts of the hybrid bus in order to make it more cost and energy effective. The main components of the hybrid bus are diesel engine, batteries, and electric motor. They can be found in the Figure 2.1 below.

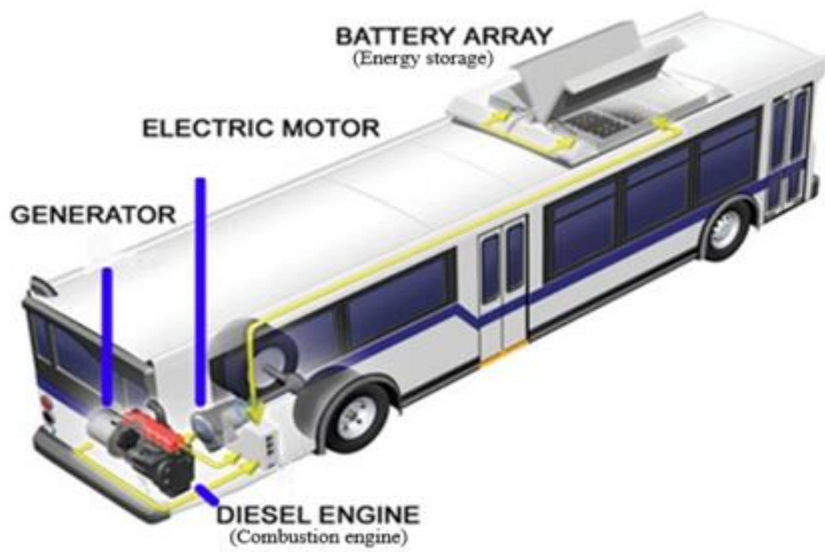

Figure 2.1: Hybrid Bus Components [2]

Description of each component can be found in the Table 2.1 below.

Component	Description
Diesel Engine	Use combustion reactions to produce energy to move to bus. Diesel engines produce greenhouse gases that cause climate change.
Batteries	Store energy using redox reactions for the future use by other components of the hybrid bus.
Electric motor	Produces torque by using the charge from the battery and provides acceleration to the hybrid bus.

Research is improving energy storage and management, so that hybrid bus becomes more energy, fuel and cost effective.

2.1 References

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3.0 THE ENVIROMENTAL BENEFIT OF USING A HYBRID BUS

The purpose of this report is to convince OC Transpo change their buses to diesel hybrid buses by showing the advantages of diesel hybrid buses over regular diesel buses that is currently being used. Sections 3.1 explains the effect of diesel engines in a diesel hybrid buses on the environment using theory of combustion reaction and greenhouse effect. Section 3.2 explains how the use of hybrid buses reduces the greenhouse gas emissions.

3.1 The Effect of Diesel Engines on the Environment

The diesel engine in a diesel hybrid bus use combustion reaction to produce energy to move the bus. During the process of combustion reactions, greenhouse gases are produced. Section 3.1.1 discusses the theory of combustion reactions and relates it to the diesel engine in a diesel hybrid bus. Section 3.1.2 describes greenhouse effect and relate it to the diesel engine in a diesel hybrid bus.

3.1.1 Combustion reactions

A combustion reaction is a chemical reaction that involves burning of a hydrocarbon with oxygen [1]. A hydrocarbon is a compound that contains carbon and hydrogen such as petroleum and natural gas [2]. The structure of the hydrocarbons methane, ethane, propane, and butane are shown in Figure 3.1 below.

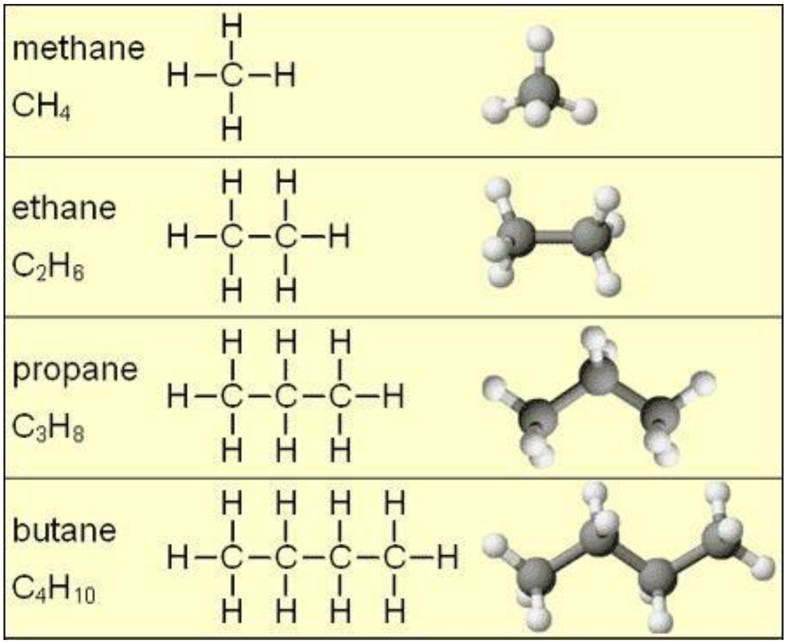

Figure 3.1: Hydrocarbons [3]

Fire is not always involved in combustion, but when it is present, flame is a good indicator of the reaction [1]. The general equation of a combustion reaction is given by Equation 3.1 below.

$$\text{Hydrocarbon} + \text{Oxygen} \rightarrow \text{Carbon Dioxide} + \text{Water} \qquad (3.1)[1]$$

The reaction shown in Equation 3.1 involves hydrocarbon and oxygen as reactants, and carbon dioxide and water as products.

An example of a combustion reaction is the combustion of Butane (C_4H_{10}) which is a substance that is usually found in lighters. The reaction involved in the combustion of butane is shown below in Equation 3.2.

$$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O \qquad (3.2)[1]$$

$$\text{Butane} + \text{Oxygen} \rightarrow \text{Carbon Dioxide} + \text{Water}$$

The combustion of butane is considered complete combustion or sometimes referred as "clean combustion", as it produces only carbon dioxide and water [1]. Another example of complete combustion is the burning process of candle wax, shown below in Figure 3.2.

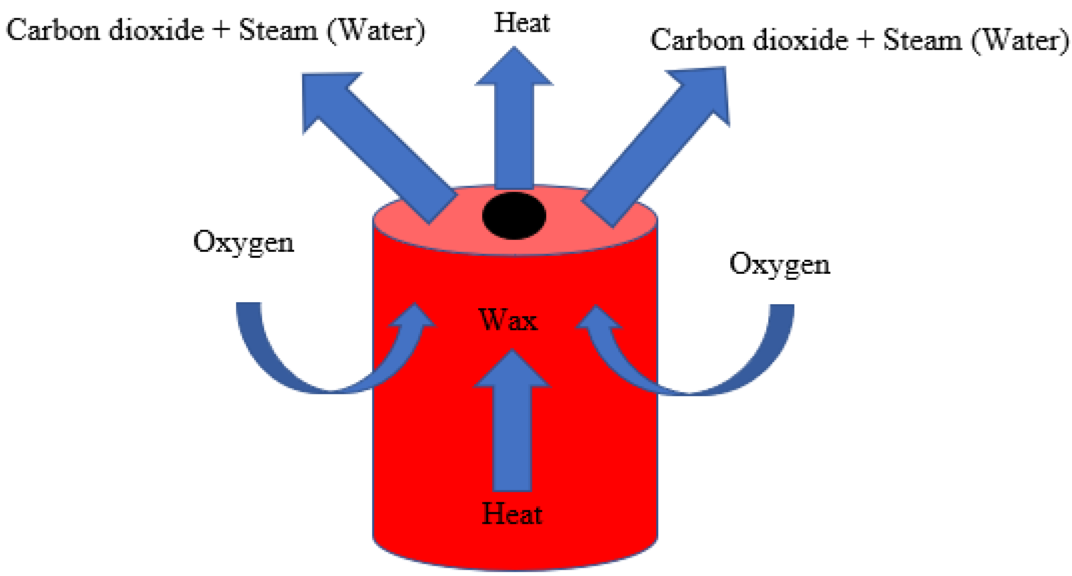

Figure 3.2: How candles burn [Youssef Ibrahim]

Figure 3.2 shows that applying heat on wax (a hydrocarbon) will make the wax react with oxygen in air producing carbon dioxide, water, and heat. The wax will keep burning until nothing remains [1].

The other type of combustion is called incomplete combustion or "dirty combustion". Incomplete combustion produces carbon dioxide, carbon monoxide, and/or carbon (soot) [1]. An example of incomplete combustion is the burning of propane which is a fuel that is commonly used in engines [4]. The chemical equation for incomplete combustion of propane is shown below in Equation 3.3.

$$C_3H_8 + 3.5\ O_2 \rightarrow CO_2 + CO + C + 4\ H_2O + \text{Heat} \qquad (3.3)[4]$$

Propane + Oxygen → Carbon dioxide + Carbon monoxide + Carbon (soot) + Water

Equation 3.3 above shows that the incomplete combustion of propane with oxygen produces carbon dioxide, carbon monoxide, carbon (soot), and water.

The diesel engine in a diesel hybrid bus is used to transform the chemical energy stored in diesel to mechanical energy, which causes the vehicle to move [5]. For energy to be released, diesel needs to be mixed with oxygen found in air and then burnt [5]. The chemical equation of diesel fuel combustion is given by Equation 3.4 below.

$$4\ C_{12}H_{23} + 71\ O_2 \rightarrow 48\ CO_2 + 46\ H_2O + \text{Energy} \qquad (3.4)[5]$$

Diesel + Oxygen → Carbon dioxide + Water + Energy

During the combustion process shown above in Equation 3.4, carbon dioxide and water are released as byproducts along with energy. The electric motor powers the bus until the bus reaches the speed of 24 km/h [6]. During cruising (more than 24 km/h), the diesel engine supplies energy for the generator, which is then converted to electrical power that will be stored in the batteries for later use [6]. During a sudden acceleration, the diesel engine and the electric motor work together to power the bus to achieve the highest efficiency [6].

3.1.2 Greenhouse effect

Carbon dioxide produced during the combustion reactions inside the diesel engine is considered one of the greenhouse gases which in excess can cause climate change by trapping heat from sun rays within the atmosphere and block heat from escaping into outer space [7]. Other examples of greenhouse gases are methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride which are all related to human activities such as burning fuel engine (diesel), deforestation, and intensive agriculture [7]. The process of trapping heat within the atmosphere is shown below in Figure 3.3.

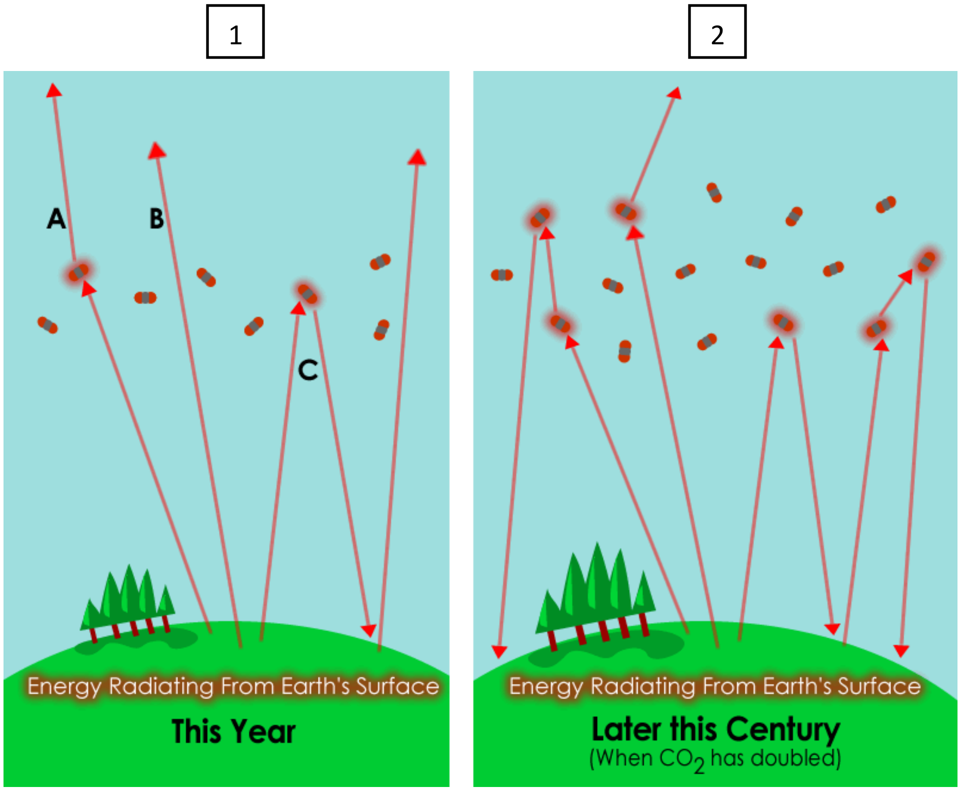

Figure 3.3: Energy radiating from Earth's surface before and after CO_2 doubles [8, modified]

Figure 3.3 shows the Earth's surface being heated using radiation energy caused by the sun [8]. Part 1 of Figure 3.3 shows that this year, some of the heat is absorbed by greenhouse gases such as CO_2 and then reflected back to space (A), some heat makes its way to the space (B), and the rest of the heat gets absorbed by the greenhouse gases then gets reflected back towards Earth's surface (C) [8]. Part 2 of Figure 3.3 shows that when carbon dioxide is doubled later this century, more heat is reflected into the atmosphere [8]. Excess greenhouse gases in the atmosphere can cause global warming, air pollution and respiratory infections [9]. Wildfires, extreme weather, and food supply disruption can also result from climate change that greenhouse gases cause [9].

3.2 How the use of hybrid buses reduces greenhouse gas emissions

Diesel hybrid buses uses the electric motor and diesel engine to supply power to move the bus. The addition of electric motor leads to less fuel consumption, and hence reducing the emissions of greenhouse gases that are released into the air, which improves the city's air quality and reduces the risk of global warming [10]. A diesel hybrid bus uses 30% less fuel than a diesel bus, which reduces greenhouse gas emissions by 30 tons of carbon dioxide per year [10].

The transportation sector contributes 29% of total U.S. greenhouse gas emissions [11]. A diesel hybrid bus compared to regular diesel bus produce 19% less carbon dioxide, 97% less carbon monoxide, 50% less particulate matter, 36% nitrous oxide, and 43% less hydrofluorocarbons [11].

3.3 References

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4.0 LITHIUM-ION BATTERY IN THE HYBRID BUS

OC Transpo is getting rid of the hybrid buses, due to the high cost of changing the batteries [1]. The purpose of Section 4 is to show how batteries work and how to improve its characteristics, so that it can last longer and be more efficient. Section 4.1 gives a basic idea of how battery works and lists all energy conversions in batteries. Improvements, that can be made to improve efficiency of the battery and hybrid bus in general are represented in Section 4.2.

4.1 Energy Storage in the Battery

To explain energy storage and energy conversions, basic components of the battery must be introduced first. Introduction to battery details can be found in Section 4.1.1 below. Principle of operation of the battery is shown in Section 4.1.2, while energy conversions that are happening in the battery may be found in Section 4.1.3.

4.1.1 Battery components

Figure 4.1 below shows main components of the battery.

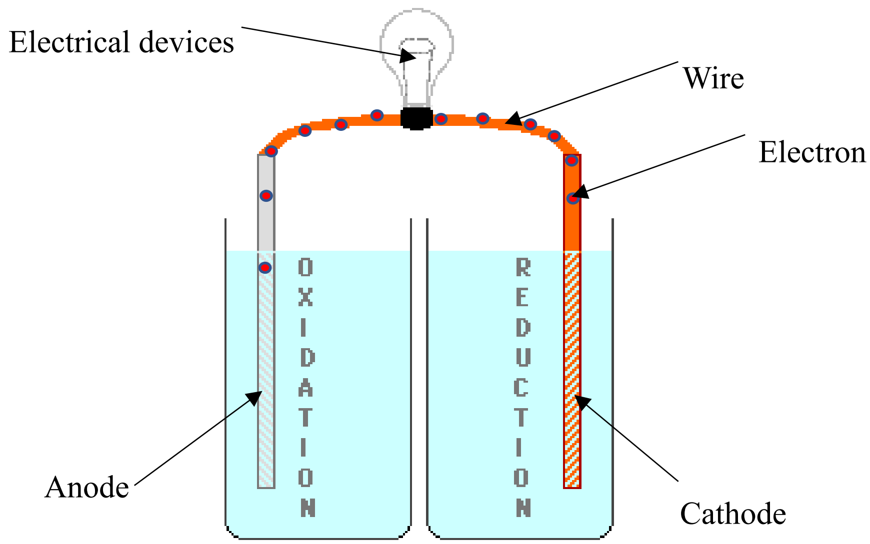

Figure 4.1: Lithium Battery [2, modified]

In Figure 4.1, electron is an elementary particle with negative charge that moves in the battery, producing electricity [2]. The anode is the plate of the battery where electrons are being released and the cathode is the plate of the battery where electrons are being absorbed [3]. The wire connects the anode, cathode, and other components. For example, it may be connected to the electric motor or combustion engine.

4.1.2 Charging and discharging

Batteries can be charging or discharging [4]. It is discharging while giving its energy to the other components of the hybrid bus, which are connected to the battery.

At the beginning of discharging that can be seen in Figure 4.1 above, all energy is stored on the left side of the battery called the anode [5]. When the battery is discharging, chemical energy is being released from the anode in the process called oxidation [5]. During oxidation, chemical substances lose at least one electron [6].

This reaction is shown in Equation 4.1 below:

$$LiC_6 \rightarrow C_6 + Li^+ + e^- + E \quad (4.1)\ [7]$$

Lithium Carbide → Carbon + Lithium + Electron + Energy

In Equation 4.1 above, only one electron is produced [3]. Energy is also released during this reaction [5].

On the other side of the battery that is called the cathode, reduction happens [2]. It can be seen in the Figure 4.1. During reduction, chemical species gain at least one electron [2]. The reduction reaction is shown below in Equation 4.2:

$$CoO_2 + Li^+ + e^- + E \rightarrow LiCoO_2 \qquad (4.2)[7]$$

Cobalt oxide + Lithium + Electron + Energy→ Lithium Cobalt Oxide

Here, the electron is being absorbed [7]. Opposite to the oxidation process, energy is consumed [5].

Discharging stops when all the electrons are transferred from the anode to the cathode [8]. There is no chemical potential left in the battery. The charging of the battery is shown below in Figure 4.2.

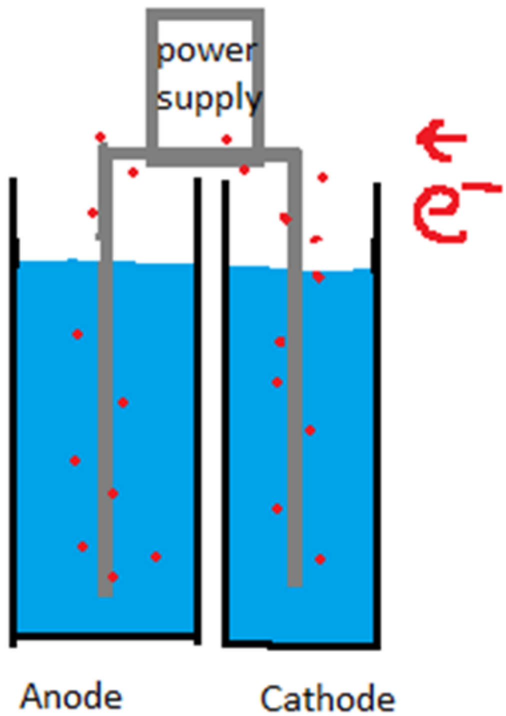

Figure 4.2: The Charging of the Battery [Vladislav Bandin]

In Figure 4.2 above, power supply is connected to the battery instead of the hybrid bus components [4]. The power supply reverses the process of discharging [4]. Electrons are going back from the cathode to the anode, so the battery stocks up the chemical energy [4]. Thus, discharging of the battery can reoccur. This is how energy is stored in the battery.

4.1.3 Energy conversions in the battery

The first law of thermodynamic states that energy cannot be created or destroyed, it can only be converted from one form to another [9]. For example, someone may say that the lamp in Figure 4.3 is creating energy in the form of light. This is not true. Figure 4.3 below shows all energy conversions in the lamp.

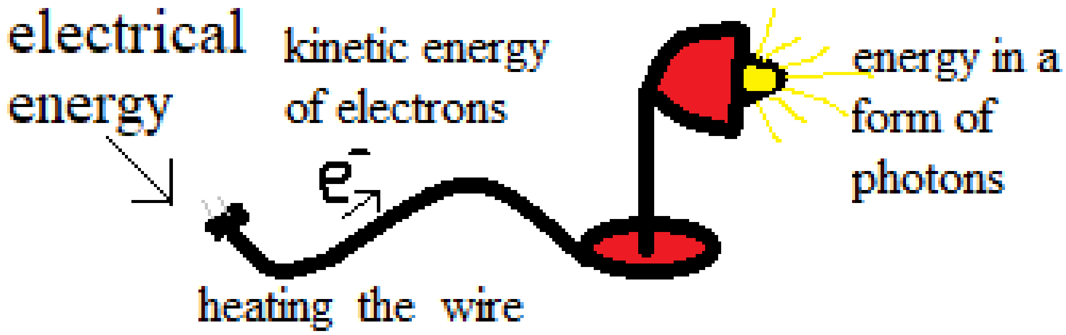

Figure 4.3: Energy Conversions in the Lamp [Vladislav Bandin]

As can be seen from Figure 4.3, energy is not created nor destroyed. The lamp takes electrical energy which speeds up electrons from the power socket. The kinetic energy of the electrons is transformed to thermal energy of the wires and energy in the form of photons. Photons are the light that people see from the bulb.

The first law of thermodynamics is shown in the Equation 4.3 below.

$$\Delta U = q - w \qquad (4.3)[9]$$

ΔU is the total change of the energy stored in the system in Joules (J), q is heat given to other objects from the system in Joules (J) and w is the amount of heat given to system in Joules (J) [9].

For example, consider room temperature water being warmed up by a kettle and poured into a cup. After a while, it becomes room temperature again, releasing 1000 J. Using the first law of thermodynamics, the amount of energy given to the water by the kettle can be calculated. Since it is known that the temperature of the water before heating and at the end of the process is the same, Equation 4.3 can be used in this way:

$w = 1000\ J - 0\ J = 1000\ J$

The amount of energy given to the system is 1000 J.

When speaking about the battery, chemical energy is being released during the oxidation reaction, as being described in Section 4.1.2 [5]. It is further converted to the kinetic energy of the electrons [10]. Electrons are moving from one side of the battery to the other, heating up the wires [10]. In other words, kinetic energy is being converted into thermal energy [10]. Electrons' speed also converts to electrical energy, which is later transformed into the mechanical energy to run the bus [10]. In the reduction reaction, kinetic energy of the electrons is transformed into chemical energy again [5].

4.2 Improvements to the Energy Storage

In most hybrid buses, lithium ion batteries are used [11]. This is a type of rechargeable battery [12]. They are more effective than other batteries but cost more [13]. In order to improve energy and fuel efficiency, ultracapacitors can be used [14]. An ultracapacitor is another type of energy storage device [15]. The ultracapacitor is shown in Figure 4.4 below.

Figure 4.4: Ultracapacitor [16, modified]

This device can work in extreme cold weather up to -40 degrees Celsius [16]. If compared with the batteries, ultracapacitors have lower maintenance requirements, save more space and last longer [16]. However, they cannot replace batteries, as they are not as effective [17].

The solution is to use batteries in series with ultracapacitors. Significant fuel economy can be reached using this method with up to 25% improvement [14].

The combination of batteries and ultracapacitors can store twice more energy than just batteries [14]. This solution also extends the batteries lifetime, as batteries are used less [17]. Thus, using this technology hybrid bus can not only be environmentally friendly, but also fuel, energy and cost effective.

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5.0 ELECTRIC MOTOR

The purpose of this part of the report is to suggest an improved electric motor for the hybrid bus. This section considers the present problems faced in hybrid buses due to its electric motor and tries to resolve it using improved features of the suggested electric motor. The electric motor suggested will help in improving the fuel-efficiency and reducing the fuel-consumption of the bus, this will help to decrease the depletion of natural resources and a reduce green-house gas emissions [1]. Electric motor is used in a hybrid vehicle to reduce the usage of the combustion engine. Electric motor is more efficient at producing torque than the combustion engine and is thus used when the vehicle is at lower speeds [1]. Section 5.1 is the explanation of the engineering theory that is used to explain the working of an electric motor. Section 5.1.1 delineates the principle of Electromagnetism; section 5.1.2 connects the engineering theory to the working of an electric motor. Section 5.2 compares the conventional electric motors to Chorus Meshcon motor, which is the recommended motor. Section 5.2.1 expands on the improvements and features of the Chorus Meshcon motor.

5.1 Torque Production

5.1.1 Principle of electromagnetism

This section explains the process through which an electric motor works. To begin with understanding the working of an electric motor, first the underlying principle behind electric motors needs to be explained. The engineering theory of electromagnetism is explained below.

Electromagnetism is the interaction between electric and magnetic fields [2]. Figure 5.1 shows the interaction between electric and magnetic fields in their waveform.

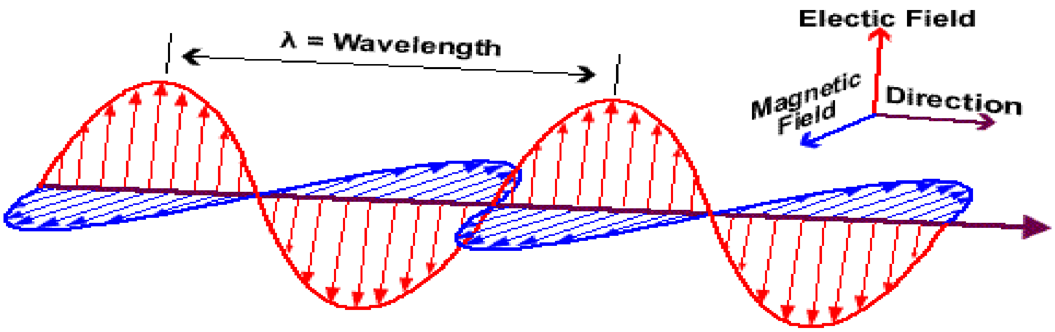

Figure 5.1: Electromagnetic wave [2]

In Figure 5.1, both electric (red colored) and magnetic (blue colored) waves propagate in the same direction perpendicular to each other. The combination of electric and magnetic waves is known as electromagnetic waves [2]. The wavelength in Figure 5.1 is the length of a wave measured between two consecutive crests (the highest point in the curve) and is represented by λ (lambda).

A physical demonstration of the interaction between electric and magnetic fields can be seen through an experiment. When electric current flows in a wire, it forms a magnetic field around it as shown below in Figure 5.2.

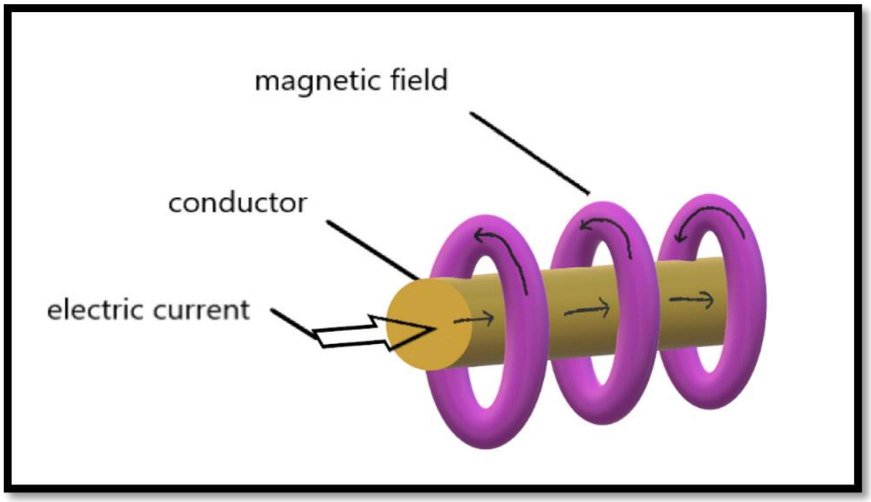

Figure 5.2: Magnetic Field by a Current Carrying Conductor [Mehran Mirza]

In Figure 5.2, the magnetic field created by an electric current carrying conductor is represented by purple circles around the conductor. The magnetic fields are formed due to the electrons flowing inside the conductor [2].

Electromagnetism or the electromagnetic force is the principle behind all electric field and magnetic field interaction [2]. A branch of electromagnetism called electromagnetic induction is the application of electromagnetism that is used in the working of electric motors. Electromagnetic induction can be simply defined as the production of electric current due to a change in magnetic field. Electromagnetic induction can be generated in two ways, when the electric conductor is kept in a moving magnetic field or when the electric conductor is moving within a constant magnetic field. A simple experiment was conducted by Michael Faraday in which he moved a bar magnet through an electric field. In Figure 5.3, voltage in the circuit changes and is seen as the fluctuation in the *galvanometer* needle.

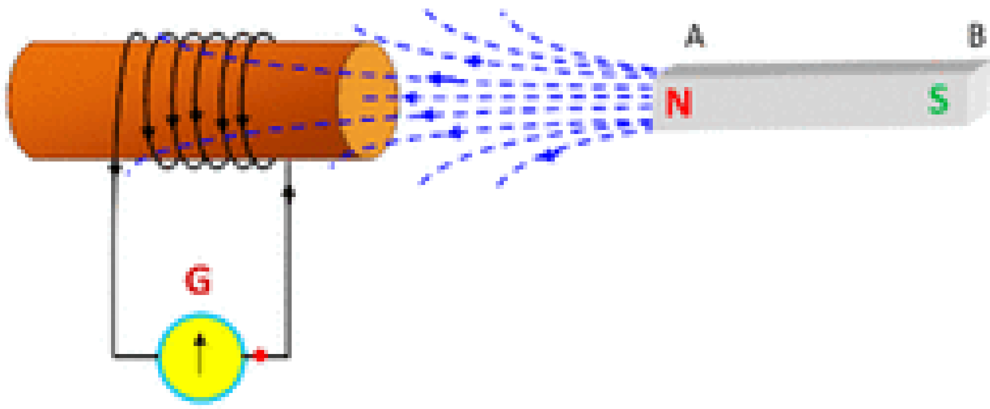

Figure 5.3: Bar Magnet Inserted through a Coiled Electric Conductor [2]

In Figure 5.3**,** when a bar magnet comes closer to the coil it produces an electric current, which is seen as a fluctuation in the galvanometer needle. In another instance, when the magnet moves away from the coil, the needle of the *galvanometer* fluctuates in the opposite direction. The conclusion Faraday made with this experiment: electric current can be produced by a change in the magnetic field.

5.1.2 Working of an electric motor

Following paragraphs will connect the theory of electromagnetic induction to the working of electric motors. First, an ordinary DC (direct current) motor is explained. Direct current is the type of electric current which flows in one direction as opposed to alternating current which alters its direction periodically. Below is Figure 5.4 of a DC motor with its components [4].

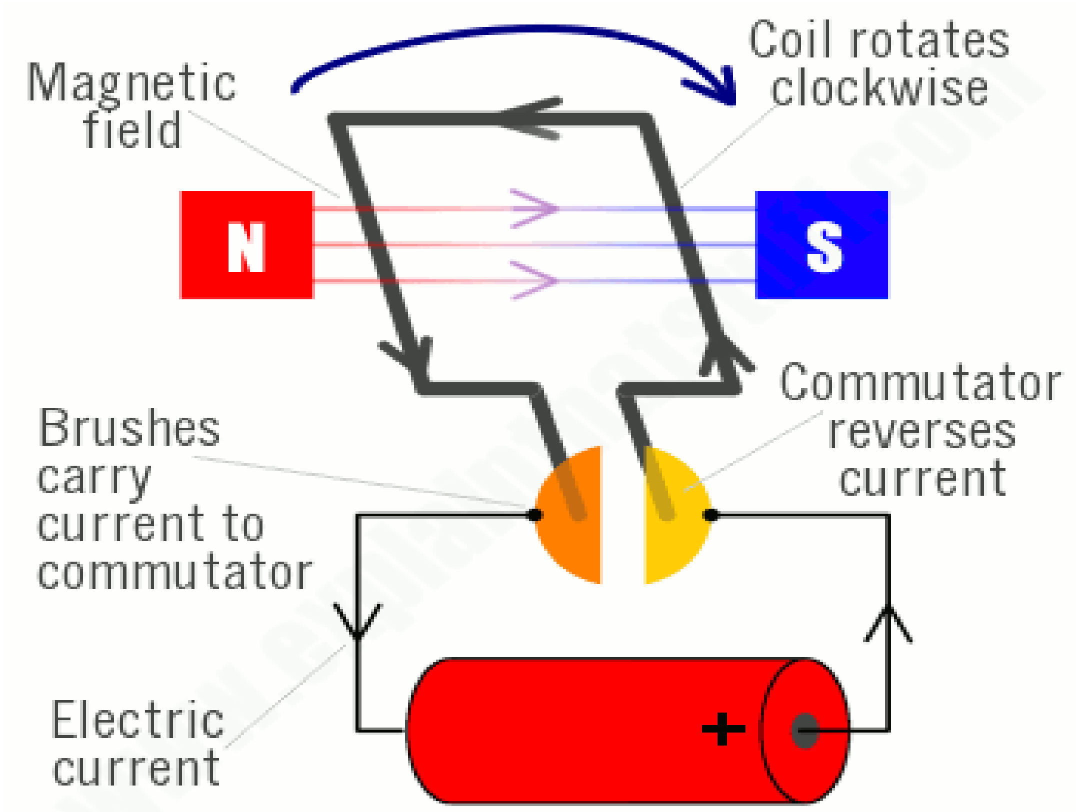

Figure 5.4: DC Electric Motor [4]

A DC electric motor is based on a rectangle loop of wire which is seen in Figure 4 turning around inside the magnetic field produced by a *permanent magnet*, depicted by N (north pole of the magnet) and S (south pole of the magnet).

The commutator (a split ring) reverses the electric current every time the wire turns over, this keeps it rotating in the same direction. When a battery is connected to the circuit shown above in Figure 4, a direct current (DC) flows producing a temporary magnetic field in the rectangular loop of wire. The temporary magnetic field repels the permanent magnet which causes the wire to flip over. The wire would flip and stop at that point and then flip back again. This is where the commutator comes into use, the current and the temporary magnetic field in the rectangular loop of wire is reversed every time the wire flips, as a result the wire keeps rotating in the same direction as long as the current keeps flowing.

The other type of motor is AC (alternating current) motor. In Figure 5.5, the internal parts of an AC motor are shown.

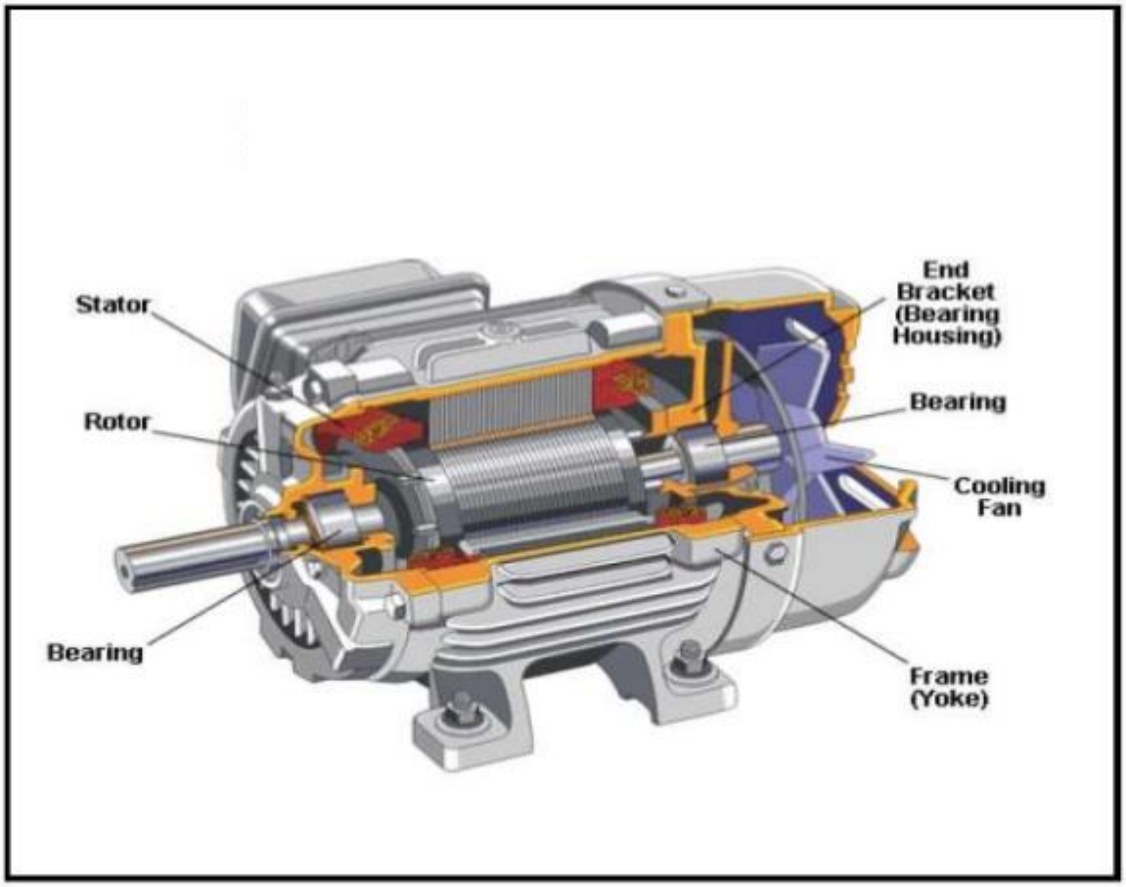

Figure 5.5: Parts of AC Motor [5]

In an AC motor there is a ring of *electromagnets* arranged outside which makes up the *stator* [5]. These are designed to produce a strong magnetic field. In an AC motor, power is sent to the outer coils that make up the *stator*. The stator coils are charged in pairs or in a sequence which produces a rotating magnetic field. The rotating magnetic field makes the rotor move and is constantly changing.

The change in magnetic field produces an electric current known as induced current as mentioned by Faraday’s law. Faraday’s law states, a changing magnetic field produces an electric field [3]. If the electric field is free to move it will produce an electric current called induced current. The induced current produces its own magnetic field. According to Lenz’s law the induced current tries to stop whatever is causing it. In this case it opposes the rotating magnetic field by rotating it. It can be explained by the rotor constantly rotating to try to catch up with the rotating magnetic field. This is done to reduce the difference in motion between the rotor and the magnetic field. The rotating magnetic field is not visible to humans. The rotor tries to synchronize its speed with the rotating magnetic field.

There are two main types of AC motors: Induction and Synchronous. The difference between them is the speed of the rotor relative to the rotating magnetic field. In an induction AC motor, the rotor lags behind the rotating magnetic field in speed, this motor is also known as asynchronous motor. Synchronous motor is a type of AC motor in which the rotor rotates in the same speed as the rotating magnetic field.

5.2 Comparison of Conventional AC motors vs Chorus Meshcon AC Motor

AC motors can be divided into two main categories as mentioned above, synchronous motor and asynchronous. Both the types are quite different from each other as evidenced by their application. Synchronous motors are mostly used in industrial applications, while induction motors are used in electric and hybrid vehicles [6]. For example, Tesla, an electric car manufacturer, uses induction motor in their electric vehicles. OC Transpo hybrid buses also used an induction motor in their hybrid buses. The recommended motor for the hybrid bus is Chorus Meshcon multi-phase AC motor, a type of an induction motor. Below, it is compared with induction and synchronous motors.

Synchronous motors can maintain constant speeds irrespective of their loads, they operate with high efficiencies at lower speeds. Drawbacks of synchronous motors is that they are expensive to maintain and cannot be started on load as their *starting torque* is zero. Also, synchronous motors cannot be used in applications requiring frequent starting of the motor [6]. Chorus Meshcon motors have starting torques which enable them to be used in frequent stop and go traffic, they do not require an external force to start-up as well.

Induction motors are long-lasting, mechanically stable motors. They have high *starting torque* and a reasonable overload capacity. Induction motors are cheap and maintenance free, making them useful for long run application and are thus preferred by vehicle manufacturers. These motors are effective where high *starting torque* is necessary like lifting weight. During constant speeds and light load conditions, induction motors draw higher current, which results in reduced efficiency. Chorus Meshcon motors, on the other hand, have software-controlled transmissions between high speed operation and low speed high torque operations. This results in better consumption of electrical power. The maintenance costs also reduce as there are lesser mechanical components due to the transmission being changed with a software [1].

5.2.1 Improvements and Features

Chorus Meshcon multi-phase electric motor is the recommended motor to be used in hybrid buses. Chorus Meshcon motor is a multi-phase AC induction motor developed by Chorus Motors [6]. This motor is being used in aerospace to drive aircrafts on the runway. Chorus Meshcon motor is currently used on Delta airline aircrafts to drive them on the runway before take-off, by using this motor Delta airlines saves fuel as Chorus Meshcon motor directly draws power from the *APU* of the aircraft, instead of using a separate intake of fuel.

Chorus Meshcon motor removes factors that cause motor heating, which limits motor performance. Chorus Meshcon motor can produce ten times the torque of a conventional electric motor [7]. It provides improved start-up or burst torque than other electric motors and this torque is used in accelerating the hybrid bus from a complete stop to an accelerated speed that can be needed to join a highway. Chorus Meshcon motor accomplishes to achieve this greater start up or burst torque by changing the layout and the software of a standard AC induction motor. The software reconfiguration enables the motor to change its behavior from a high-torque low-speed motor that is used when accelerating the hybrid bus from complete halt to a low-torque high-speed motor, to be used when cruising at constant speed. Chorus Meshcon also provides advantages such as: requires less caliber cooling system and simpler transmission than conventional hybrid buses [7]. Thus, reducing weight of the hybrid bus also saving expenses. Overall, Chorus Meshcon motor significantly improves the current induction motor that is used in hybrid buses. It reduces fuel consumption thus saving travel costs which leads to a reduction in OC Transpo ticket prices.

5.3 Glossary

Alternating current: Type of current used to power AC motors. [1]

APU: Axillary power unit is a jet engine used in aircrafts. It provides power to start the main engines. Chorus Meshcon motor runs on the power provided by APU.[8]

Electromagnets: Magnets in which magnetic field is created by an electric current, in an AC motor the stator is made up of electromagnets. [5]

Galvanometer: Device used to measure small changes in electric current. It is used in the experiment to show that electric current is generated by a change in magnetic field. [5]

Staring torque: Maximum rotational force that can be produced by a motor to start rotational movement of the load [1]

5.4 References

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6.0 CONCLUSION

Hopefully, the findings in this report will help OC Transpo in deciding to restore the hybrid bus program and will convince them to implement hybrid buses back into their fleet. Ultracapacitors working together with batteries improves energy storage and reduces maintenance costs, while better electric motor allows to reduce fuel usage. Overall, it increases cost, energy, and fuel efficiency of the hybrid bus. Thus, it becomes even more environmentally friendly.

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