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Conference Article

Electric Motor Selection Criteria for Traction System in Construction Machines

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Abstract

Recent developments in electric motors in construction machinery and the automotive sector's trend towards electric traction in recent years are among the factors triggering and influencing the shift towards electric traction in construction machinery. There is no doubt that electric construction machinery will be the first choice for urban operations in the future, but many research and development efforts are still ongoing to dominate the market. Electric motors are the most important components of power transmission systems in electric machines. The trend towards increasing power density and efficiency in power transmission systems contributes to different designs and improvements in basic electric motor topologies.

This article provides an insight into the selection of electric motors to be used in power transmission components of electric construction machinery and allows for the comparison of different electric motors.

Keywords: Electric Motor, Traction System, Construction Machines

1. Introduction

In recent years, with the rapid advancement of technology and the increasing impact of factors such as air pollution, depletion of petroleum resources, and global warming, intensive efforts have been made worldwide to develop alternative energy sources and produce sustainable and environmentally friendly solutions. In developing countries and large cities, the harmful emissions of diesel engines in construction machinery, such as Particulate Matter (PM), nitrogen oxides (NOX), CO, and sulfur dioxide, as well as the noise pollution caused by construction machinery operating in city centers, contribute to environmental pollution and threaten human health [2]. Due to reasons such as zero emissions and lower noise levels compared to diesel systems, as well as higher efficiency, electric systems are increasingly being used as a viable option for electrification in construction machinery. Depending on the traction configuration or expectation in construction machinery, AC/DC motors can be used. In recent years, with increasing demand, it is observed that different types of DC and AC motors have been developed and continue to evolve. Careful consideration should be given to determining a specific electric motor for traction in construction machinery. The motors used in construction machinery are quite different from other motor applications. Specific definitions are required for the motor to be used, including the weight of the machine, the target machine speed, efficiency, cost, reliability, innovation, controllability, regenerative braking, durability under harsh working conditions, low maintenance requirements, and integration with other components. This article presents a comparison of the most popular electric motors used in the power transmission system of tracked mini wheel loaders in construction machinery.

2. Electric Power Traction System

The concept of power traction mechanism is a subsystem of the construction machinery concept and significantly influences the energy consumption and thus the range of an electric construction machine. The power traction system consists of a battery, power electronics, electric motor, and gearbox [3, 4, 5, 6, 7]. Due to the reduction of moving parts in the electric power traction system, it is more flexible compared to the architecture of traditional internal combustion engine machines. Instead of a hydrostatic or transmission system, a simple gear transmission box is used in the power traction system [8].

2.1. Electric Power Traction System Architecture,

The architecture of the electric construction machine's power traction system refers to the arrangement of energy sources, transmission components, and their placement within the chassis. The energy flow is facilitated by flexible electrical cables and minimal moving connections. Depending on whether the construction machines are wheeled or tracked, they have different power transmission systems. The power traction system of construction machines equipped with tracked walking systems, such as mini wheel loaders, will be primarily examined. It has a simple architecture powered by one or more electric motors [9]. The fundamental components of the electric power traction system are the electric motor, controller, power source, and transmission system, as shown in Figure 1.

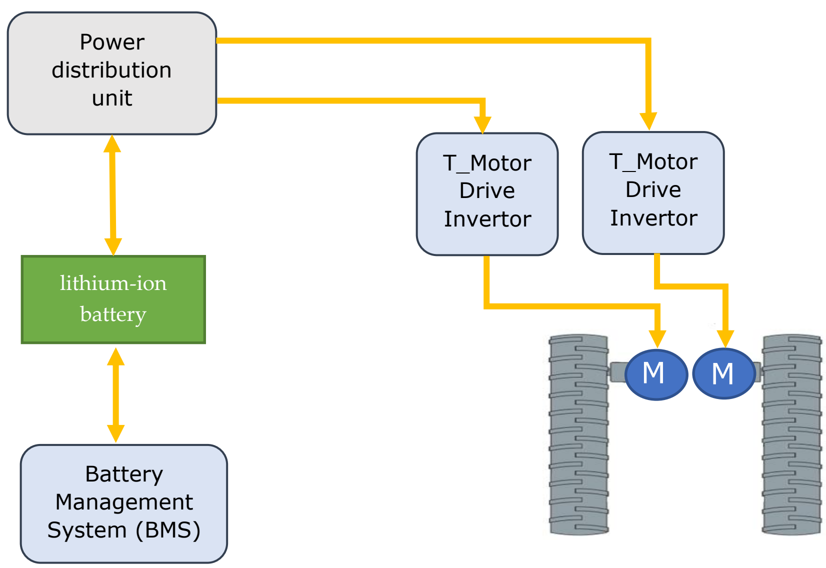

Figure 1: Basic Electrical Power Traction System Scheme

The power traction system of tracked construction machinery may vary depending on the type of machine they are used in. These systems are the part that supports the weight of the machine and provides movement. The track system attached to both sides of the machine is connected to the main chassis of the machine. This system, carried by the machine chassis, also prevents some of the impacts coming to the chassis in certain types of construction machinery. The chassis functions somewhat like a suspension system. There is a simple gearbox between the electric motors and the track system. This is because it is necessary to transmit more torque to the track section. Batteries constitute the energy storage providing power to the electric motors. With the increase in electric vehicles, there have been advancements in battery technology as well, leading to the emergence of batteries with different chemical properties. Development and research in battery technology are still ongoing.

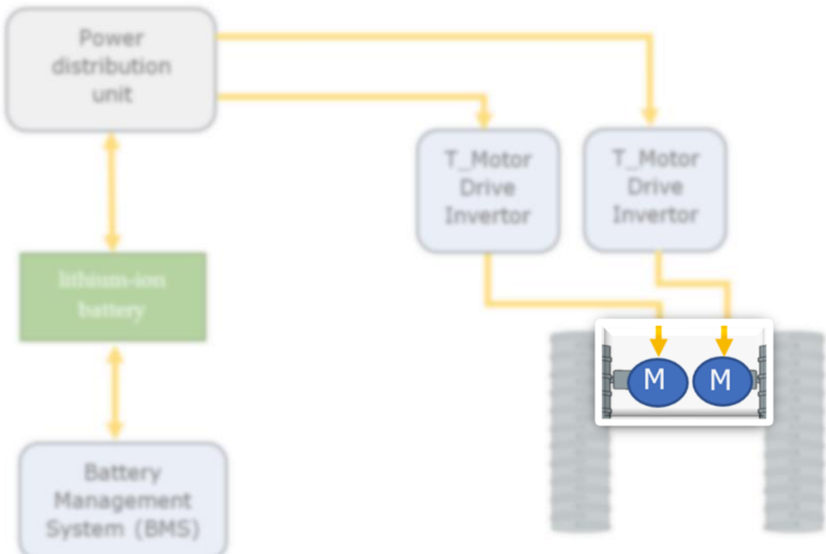

Figure 2: Power Train Electric Motors

The electric motor component of the power traction system operates by receiving energy from the battery through a power electronics control system. Power electronics also communicate with other control elements to regulate the electric motor based on user inputs such as throttle or brake pedal positions [10, 11, 12, 13].

"In construction machinery, the types of electric motors used vary, but some commonly used types include:

Alternating Current (AC) Motors: AC motors are typically known as asynchronous motors or permanent magnet synchronous (PMSM) motors. Asynchronous motors are widely used in applications such as traction systems for electric vehicles, while PMSM motors are generally preferred for higher performance and efficiency.

Direct Current (DC) Motors: DC motors come in brushed or brushless varieties. Brushed DC motors control the rotor's magnetic field through brushes, while brushless DC motors operate without brushes. DC motors can be used in certain construction machinery due to their simpler structures and ability to provide high torque at low speeds.

Brushless DC Motors: Brushless DC motors do not use brushes, unlike brushed motors, and therefore require less maintenance. These motors typically operate more efficiently

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and quietly, making them suitable for various applications such as construction machinery.

Other Specialized Motors: Some specialized construction machinery may use specially designed motors to meet specific requirements. For example, hydraulic motors are used in some construction machinery, while linear motors or stepper motors may be preferred for certain applications.

These types of motors have different features and advantages to meet the various needs of construction machinery. Each is most suitable for specific applications, depending on the requirements and performance expectations of the machine to be used."

2.2. Battery Technology

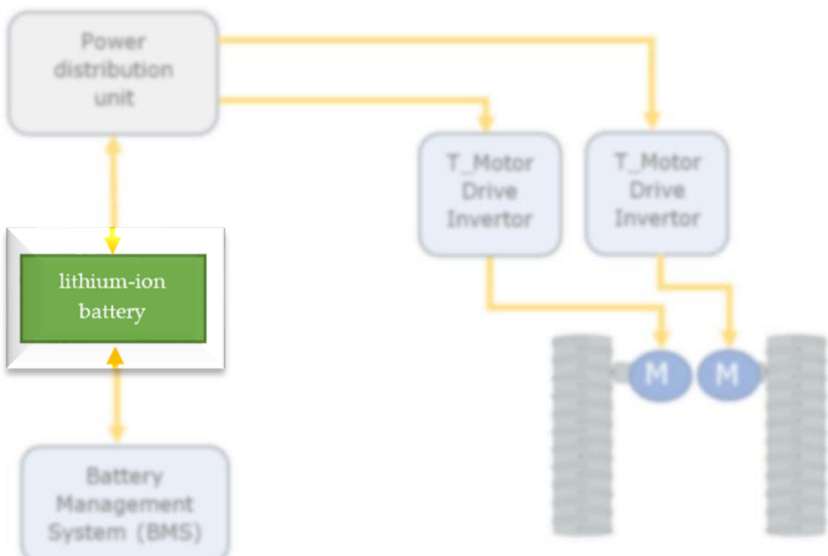

Figure 3: Power Train Battery

The greatest technological challenge in the electrification of future vehicle concepts lies in the development of powerful yet cost-effective battery systems [14].

The cell chemistry used in electric vehicles is primarily categorized as follows:

- Lead-Acid Battery
- Ni-Cd Battery
- Nickel-Metal Hydride (Ni-MH) Battery
- Li-ion Battery
- Li-Po Batteries
- Li-Titanium Batteries (LTO)

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- Al-air Battery (Technology of the Future).

Due to the safety concerns of vehicles and battery packs, the use of lead-acid batteries in electric vehicles has significantly decreased, and Li-ion batteries have become the most preferred option in electric vehicles in recent years. The cathode of these batteries is mostly used as Li composites. Depending on the chemical properties of these batteries, the specific energy of each cell varies between 150~260 $\frac{Wh}{kg}$.

The most reliable Li-ion cell chemistry currently used in electric vehicles is LFP or Lithium Iron Phosphate, and the emerging alternative chemistry is NMC or Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2). Both chemistries offer good cycle life and durability in terms of performance [15].

2.3. Power Electronics Control System

The electronic control units and motor drivers in power electronics use predefined communication standards. Typically, the CAN system is used as the primary communication standard. Some other communication systems include:

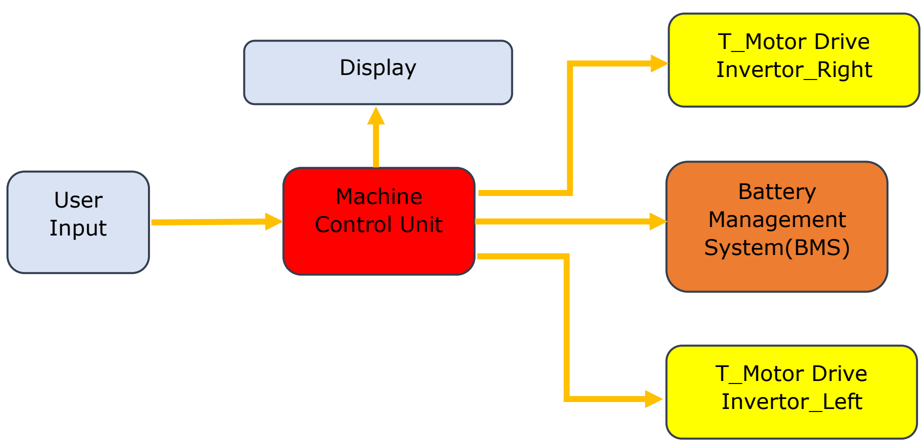

Figure 4: Basic Electronic Control System Scheme

Modbus an [illegible] by auxiliary vehicle components that do not require real-time data communication.
Protocols like CHAdeMO and CCS play a crucial role in fast charging.
ISO15118 enables bidirectional charging and vehicle-to-grid (V2G) integration.
Ethernet serves as a one-stop solution for high-bandwidth data communication needs like video streaming, infotainment systems, and ADAS.
Wi-Fi and Bluetooth facilitate integration with smartphones or devices.

In the communication control system, the machine's control unit sends instructions to the motor drivers based on user commands for moving the machine forward, backward, right, left, or braking. The motor driver, according to the instructions received from the machine's control unit, ensures the electric motor operates most efficiently based on the specific algorithm defined for the motor type. Power transmission systems have specially developed control strategies and algorithms [16].

In Figure 4, the energy received from the onboard charger in the electronic control system of the electric power transmission system is stored in the battery control system managed by the battery. Energy flows from the battery through electric cables to the motor controller DC/AC inverter. The inverter communicates with other electronic control units to control the power transmission motor.

2.4. Mechanical Transmission

The electric motor operates within a high-speed range and provides high torque values at low speeds. To obtain the necessary torque for machine traction, a single-speed gearbox is required. The ratio in the gearbox is crucial when calculating the speed and traction power required for the machine when selecting an electric motor. The ratio of the gearbox selected determines the operating speed and torque of the electric motor at its most efficient operating speed.

2.5. Electric Motors

Electric machines are designed to convert electrical energy into mechanical energy or vice versa. They are used to provide torque and power to the power transmission system. The energy conversion efficiency of an electric machine ranges from 85% to 96% [16]. Compared to traditional internal combustion engines, an electric motor provides higher nominal power, typically two to three times higher, with higher torque and power density at the start-up stage. During braking, it is used in regenerative mode to slow down the machine by charging the storage system [16].
The requirements of the propulsion system are as follows [17, 18, 19]:

High power density and high instantaneous power.
Fault tolerance.
High power requirement at high speeds for cruising.
High torque requirement at low speeds for start-up and climbing.
The machine must operate with high efficiency over a wide range of torque and speed.

Fast torque response.
High efficiency even during regenerative braking.
High robustness and reliability for various adverse conditions and vehicle operating conditions.
Optimal cost.
The requirement for high torque at low speeds for start-up and climbing is decided by comparing the cost and availability of motor controllers and power converter technology.

3. Electric Motors Used in Power Traction

Electric motors used in power traction include direct current (DC) motors and alternating current (AC) motors. Critical requirements for selecting an electric motor include higher power density and torque, variable speed range, high efficiency, high reliability, lightweight, small size, low noise level, and cost-effectiveness. Previously, DC motor drives were the preferred choice for electric vehicles, but due to inefficiency and unreliability, DC motors are now less preferred [20]. Induction and permanent magnet (PM) types have become more preferred with the development of power electronics systems [21].

3.1. Brushed DC Motors

Brushed DC motors provide high torque at low speeds and have a suitable torque-speed characteristic. Due to their brush and commutator structure, they are bulky and are almost not used in power transmission systems due to their disadvantages such as low efficiency, low reliability, and requiring costly maintenance.

$$T[N \cdot m] = \frac{Motor\ output[P]}{2 \cdot \pi \cdot N[rev/\ min] \cdot 60}$$

Here, T represents torque in Newton meters and N represents speed in revolutions per minute.
From the above relationship, torque and speed are inversely proportional to each other, and therefore, a DC motor has low torque at high speeds and vice versa. While the speed-torque characteristics can meet traction power requirements, they may not meet those of Electric Vehicles.

3.2. Asynchronous Motors

Three-phase asynchronous motors offer advantages such as reliability, ability to operate in harsh environments, less maintenance, and lower cost compared to DC motors due to the absence of commutator brushes used in DC motors. In an asynchronous motor, there are two parts: the stator and the rotor. The rotor rotates at synchronous speed in the air gap between the rotor and stator, inducing rotor currents to create a magnetic field in the stator, which is fed by three-phase alternating current. There is a phase difference of 120 degrees in three-phase current. The currents induced in the rotor conductors allow the formation of a magnetic field in the rotor. Two magnetic fields operating at different speeds generate torque [22].

An increase in the speed of the asynchronous motor leads to an increase in the back electromotive force (EMF) and reactive voltage of the motor, resulting in a poor power factor. This decrease in power factor can be compensated for using dual inverter with one of the inverters connected to a floating DC link capacitor bank. This will result in achieving unit power factor for the main DC line connected to the source, leading to an expansion of the motor's constant power region [22].

High Initial Cost: Synchronous motors typically involve high-tech components and come with a higher cost. This can increase the initial cost of electric vehicles.
Control Challenges: Synchronous motors require complex control algorithms. This may necessitate expertise for proper motor operation and performance optimization.
Cooling Requirement: Due to their high-power density, synchronous motors may encounter temperature rise that requires effective cooling. This can lead to the necessity and cost of additional cooling systems.
Low-Speed Issues: Some synchronous motors may experience torque loss at low speeds. This can be significant, particularly when electric vehicles require low-speed maneuvering.
High Precision: The production of synchronous motors requires high precision. This may increase production costs and the likelihood of production errors affecting performance. These disadvantages may limit the use or impact the application scenarios of synchronous motors. However, with continuously advancing technology and engineering efforts, many of these disadvantages can often be mitigated or overcome.

3.3. Permanent Magnet Synchronous (PMSM) Motors

Permanent Magnet Synchronous Motors (PMSMs) are a widely used type of electric motor in electric vehicles and construction machinery. These motors are AC (alternating current) motors with rotors and stators containing permanent magnets.

Some fundamental features of PMSMs include:

High Efficiency and Reliability: PMSMs provide high efficiency and are long-lasting. The use of permanent magnets minimizes energy losses and ensures the motor operates more efficiently.

High Power Density: Despite their compact size, PMSMs can generate high power. This is advantageous for vehicles such as construction machinery that operate in limited spaces.

Full Torque at Low Speeds: PMSMs can generate full torque even at low speeds. This feature enables construction machinery to operate powerfully at low speeds.

Responsive to Load Changes: PMSMs can respond well to rapid changes in speed. This facilitates adaptation to various operating conditions of construction machinery.

Low Noise Levels: The use of permanent magnets and smooth operating principles result in low noise levels for PMSMs.

High Performance: PMSMs are generally considered high-performance motors. They can operate powerfully and stably at high speeds.

These features make PMSMs an ideal choice for the traction system of construction machinery. Their strong performance, low maintenance requirements, and long lifespan enhance the efficiency and durability of construction machinery.

Torque/Speed Relationship:

This relationship expresses the output torque and speed of the motor. It is typically expressed by the following formula:

$$T = \frac{P}{2 \cdot \pi \cdot N}$$

Here:

T represents the torque (Nm).

P represents the output power of the motor (Watt).

N represents the speed of the motor (rpm or rad/s).

Efficiency Calculations:

Motor efficiency is typically expressed as the ratio between input and output powers:

Efficiency (%) = Output Power / Input Power × 100

Power Loss Calculations:
Motor power loss is calculated as the difference between input and output powers:
Power Loss = Input Power − Output Power

Magnetic Flux Calculations: Magnetic flux is typically calculated as a function of stator and rotor currents. Magnetic flux is a measure of the motor's magnetic field and generally determines the magnetic field intensity and performance of the motor.

These formulas are used during the design, analysis, and performance evaluation of PMSMs. These calculations are important for optimizing the motor and achieving the desired performance.

Permanent Magnet Synchronous (PMSM) disadvantages:

High Initial Cost: PMSM motors typically have a higher initial cost compared to other motor types due to the use of magnetic materials and special design requirements.

High Sensitivity: PMSM motors must be carefully installed to ensure that the magnetic field of the magnets is not affected by external factors. This can make production and assembly processes complex and require additional sensitivity.

High Temperature Sensitivity: PMSM motors may lose performance if the magnets are exposed to high temperatures. Therefore, temperature control and cooling measures may be required.

Risk of Power Loss: In PMSM motors, there is a risk of power loss if the magnets demagnetize or become damaged. This can affect the efficiency and performance of the motor.

Difficult Fault Repair: Due to the complex structure and special design requirements of PMSM motors, repairing faults can be difficult and time-consuming. This can increase maintenance and repair costs.

These disadvantages should be considered during the use and maintenance of PMSM motors. Each situation may vary depending on specific usage scenarios.

3.4. Switched reluctance motors

Switched reluctance motors are a type of electric machines commonly used in construction equipment. These motors are a type of induction motor, where their rotors interact with a magnetic field to produce a rotational motion.

Switched reluctance motors are typically preferred for applications requiring high torque. They can provide high torque at low speeds and are also suitable for constant-speed operation. Since these motors rely on the interaction of their rotors with a magnetic field, they require an external power source to generate the rotational motion.
Switched reluctance motors are favored in industrial applications for being robust and durable. Additionally, they are popular due to their low maintenance requirements and long lifespan. These motors are commonly used in conveyor systems, pump systems, compressors, and similar applications.
The advantages of switched reluctance motors include high torque, low cost, simple construction, low maintenance requirements, and a wide range of applications. However, they also have some disadvantages, such as limited ability to operate at constant speeds and reduced efficiency at high speeds. Nevertheless, in the right application, switched reluctance motors can be a reliable and effective option.

$$T = \frac{P}{2 \cdot \pi \cdot N}$$

Here:
T represents the torque in Newton meters.
P represents the output power of the motor in Watts.
N represents the speed of the motor in revolutions per minute (rpm).
This formula expresses the relationship between the output torque, output power, and speed of the motor. Torque is proportional to the output power and inversely proportional to the speed. This formula is used to assess the performance and optimize the design of switched reluctance motors in academic contexts.

4. Working Modes

Mini backhoe loaders typically have various operating modes, which make them versatile for different tasks. Typically, the main operating modes of mini backhoe loaders are as follows:
Excavation Mode: This mode optimizes the mini backhoe loader for digging operations using the backhoe side. It is used to remove materials such as soil, sand, gravel, etc., using a bucket or other excavation equipment. The power transmission system is not used in this operating mode.

Loading Mode: Loading mode is optimized for the mini backhoe loader to load materials. In this mode, the loader is typically used to load materials onto a truck or carrier.

Transportation Mode: In transportation mode, the mini backhoe loader is used to transport materials from one point to another. The machine's movement is optimized in this mode, and the transported load is held steadily.

Leveling Mode: Grading mode is used for leveling or smoothing the ground at the worksite. In this mode, the mini backhoe loader performs compaction or leveling operations on the ground surface.

Other Special Modes: Some mini backhoe loaders may have additional modes to meet special job requirements. These could include special modes for tasks such as snow plowing, grass cutting, or material mixing.

These operating modes enable the mini backhoe loader to be flexibly used for various tasks and perform a variety of duties at the worksite.

4.1. Leveling Mode Test

Leveling is a widely used technique in various industries such as construction, road construction or landscaping to ensure that the work site is smooth and meets the desired specifications. It is the operating mode of the power transmission system where very intense power and torque demand is present. In this mode, testing was carried out in a designated area. The power and torque data required by the power transmission system for the test were obtained.

In figure 5,6.

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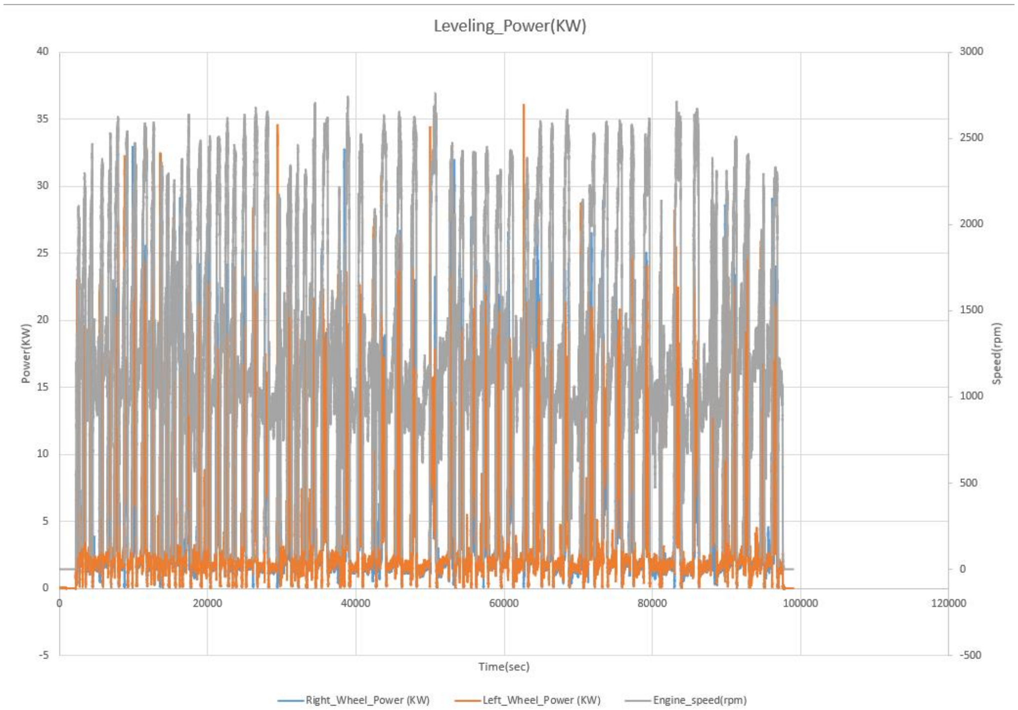

Figure 5: Leveling Power Test Results

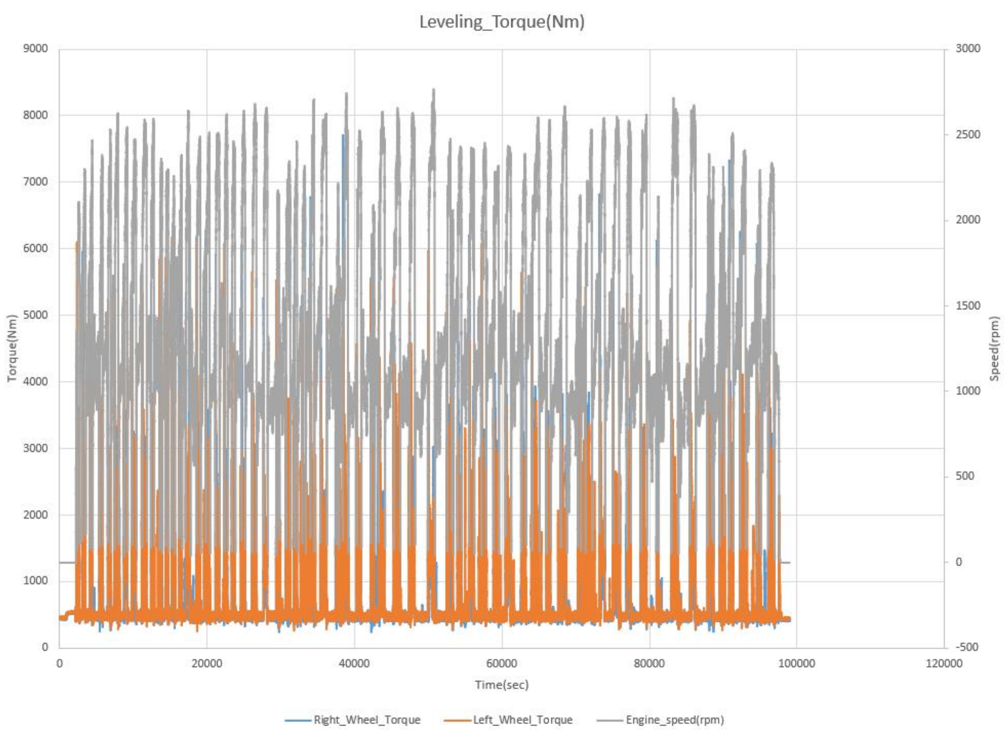

Figure 6: Leveling Torque Test Results

4.2. Loading Mode Test

Loader mode, the mini excavator loader machine is typically used to load materials onto a truck or carrier.

The loading process typically involves the following steps:

Material Collection: Initially, the mini backhoe loader collects the material to be loaded using a bucket or other appropriate equipment. These materials may include soil, gravel, sand, construction debris, or other portable materials.

Loading Operation: The mini backhoe loader is used to load the collected materials onto the target vehicle. The bucket is brought close to the target transport vehicle, and the material is gently discharged.

Balance and Control: During the loading operation, the operator typically carefully controls to ensure the balance of the load. It is important to distribute the load evenly and load it onto the transport vehicle without causing damage.

Material Dump: After the material is loaded, the mini backhoe loader can dump the material to the intended area when necessary.

In the loading mode operation, the power and torque data required for the power transmission system are indicated by the test figure 7,8.

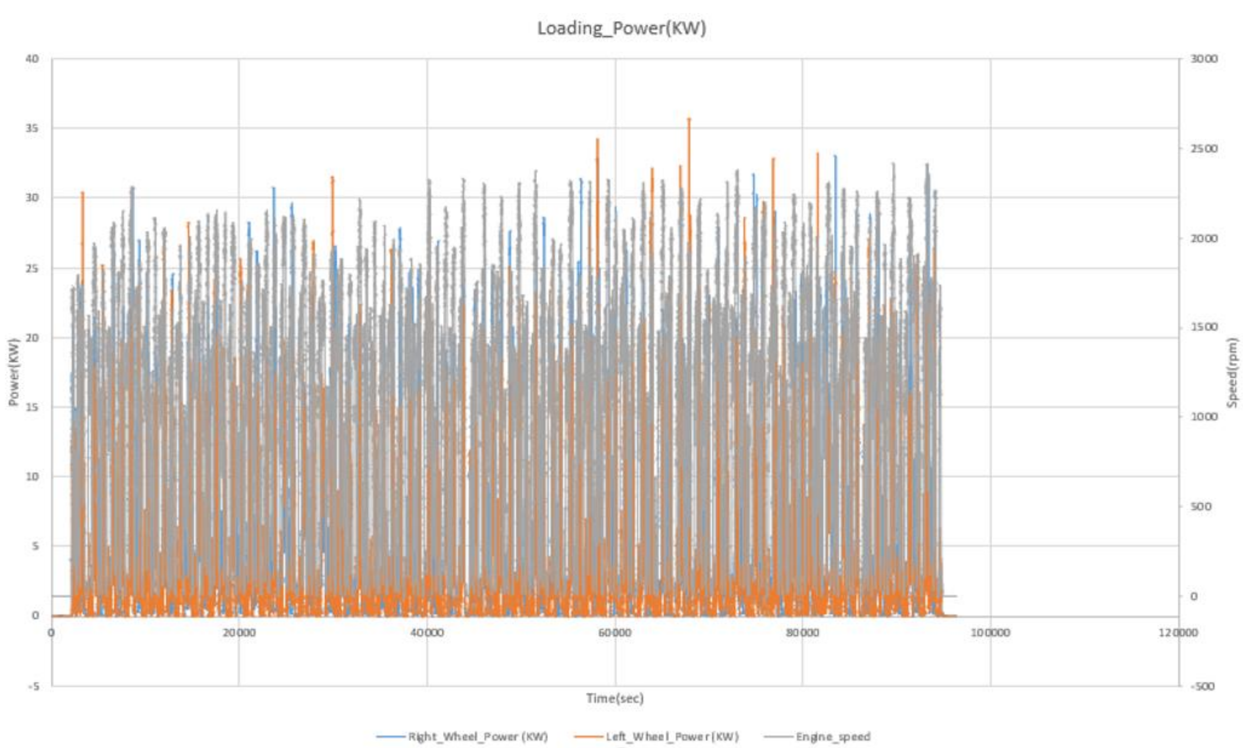

Figure 7: Loading Power Test Results

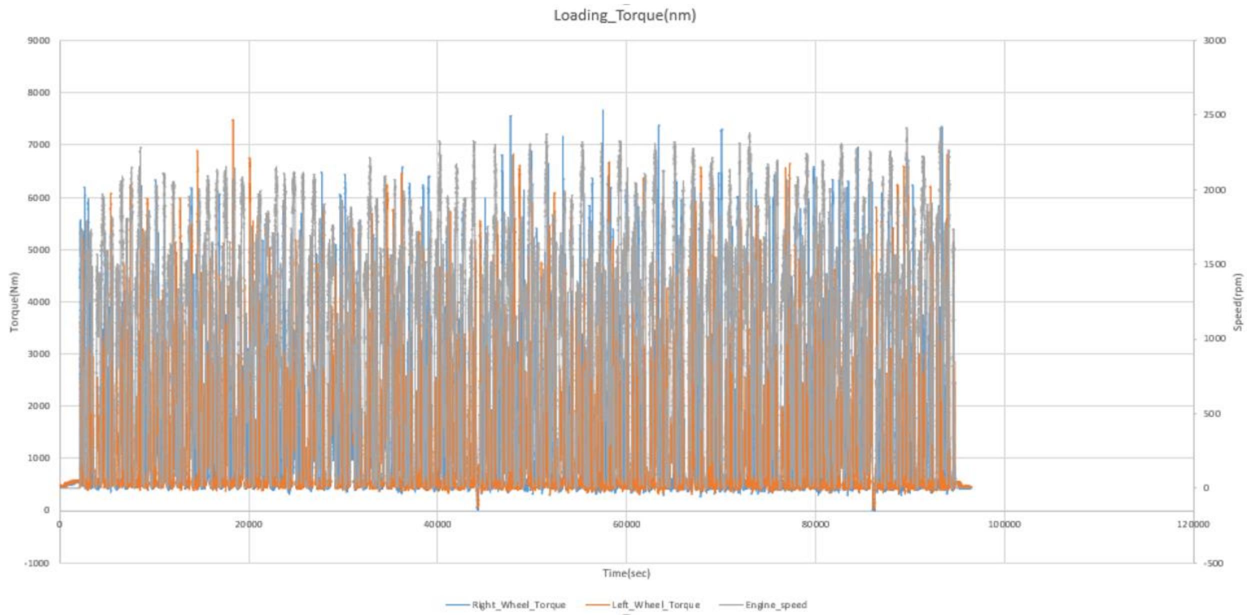

Figure 8: Loading Torque Test Results

4.3. Transportation Mode

The transportation operating mode of mini backhoe loader machines is a mode of operation that enables the safe and efficient transportation of materials from one point to another. In this mode, factors such as loaded, unloaded, and incline, flat ground affect the power and torque demands of the power transmission system, which are indicated in the test results in figure X.

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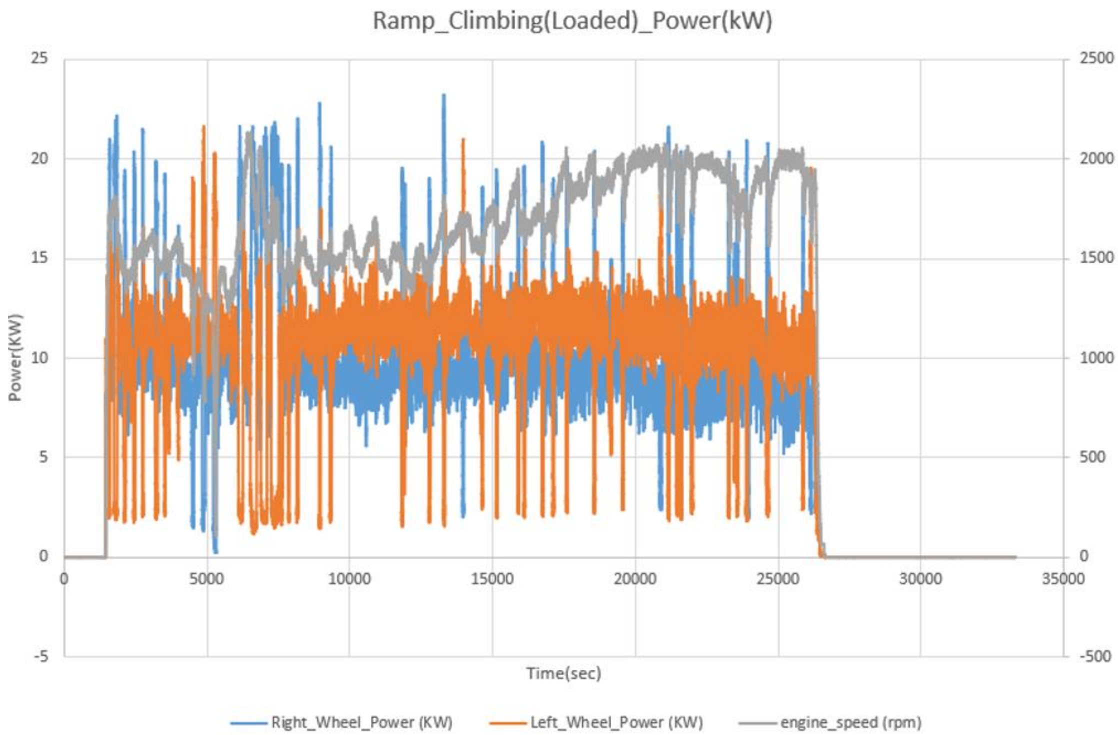

Figure 9: Ramp Climbing Power Test Results (loaded)

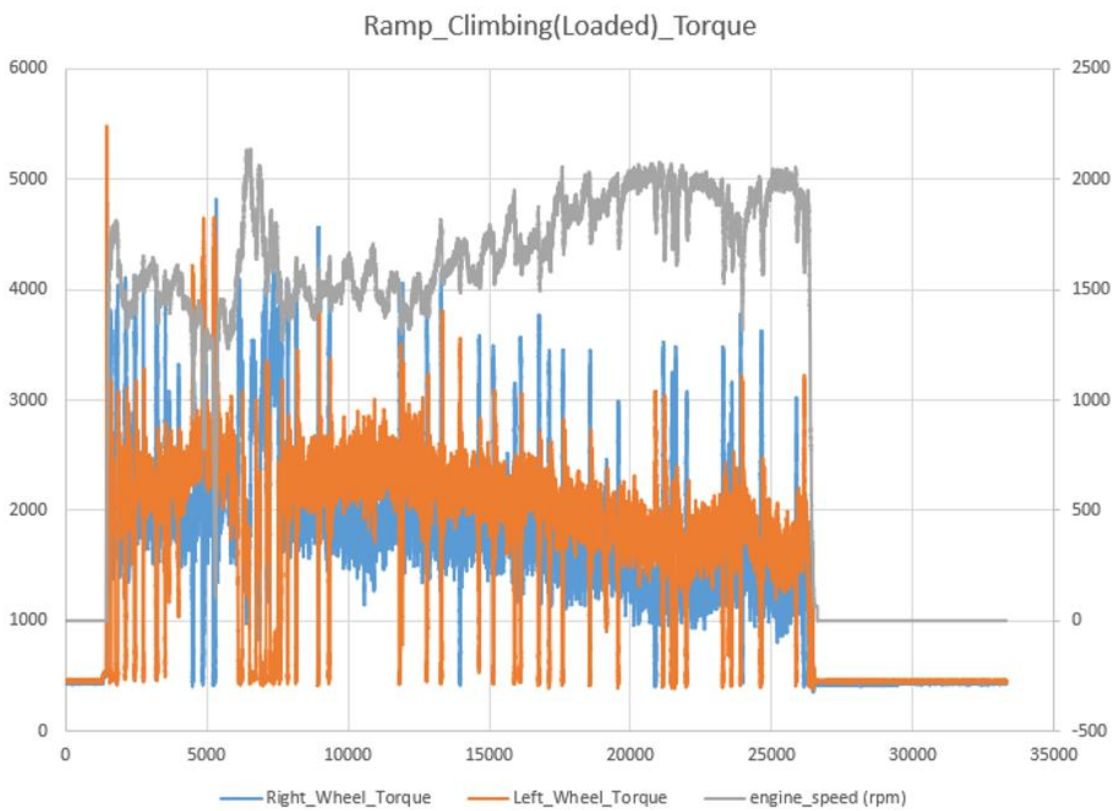

Figure 10: Ramp Climbing Torque Test Results (loaded)

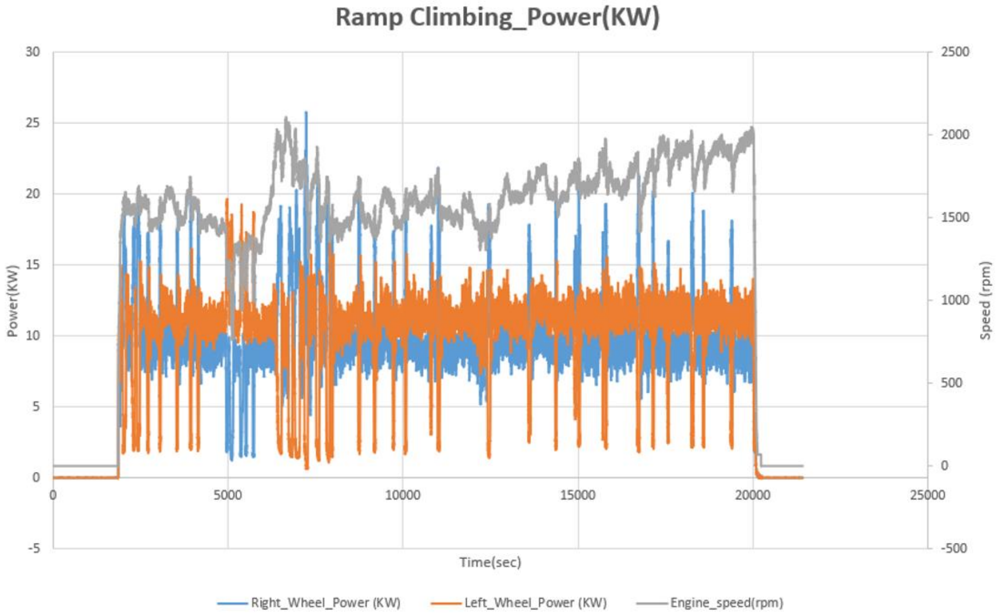

Figure 11: Ramp Climbing Power Test Results

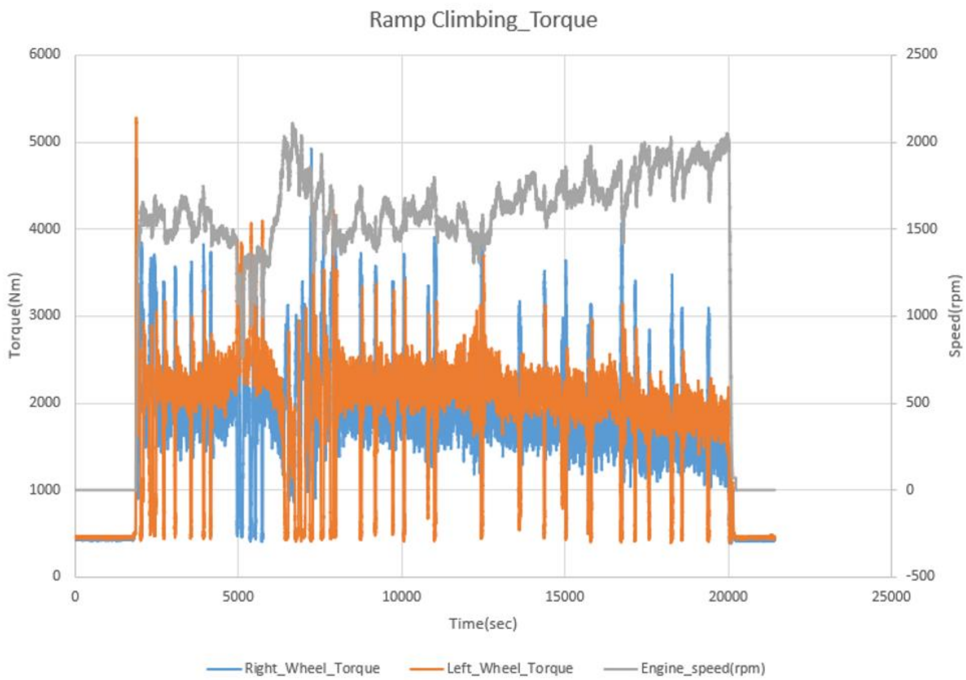

Figure 12: Ramp Climbing Torque Test Results

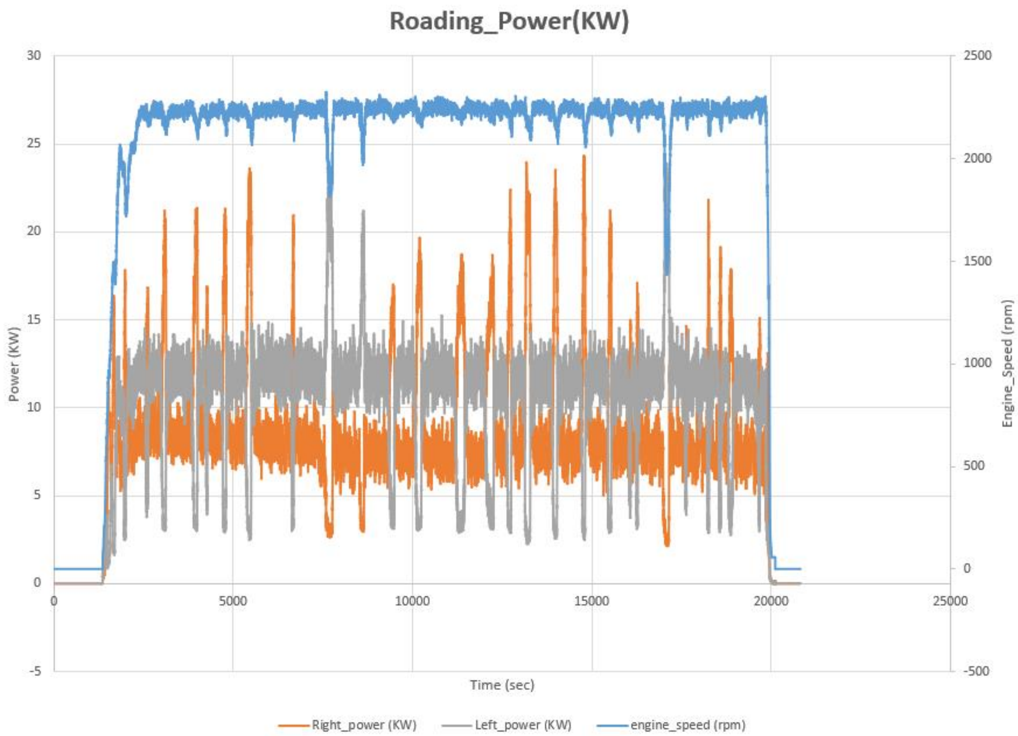

Figure 13: Roading Power Test Results

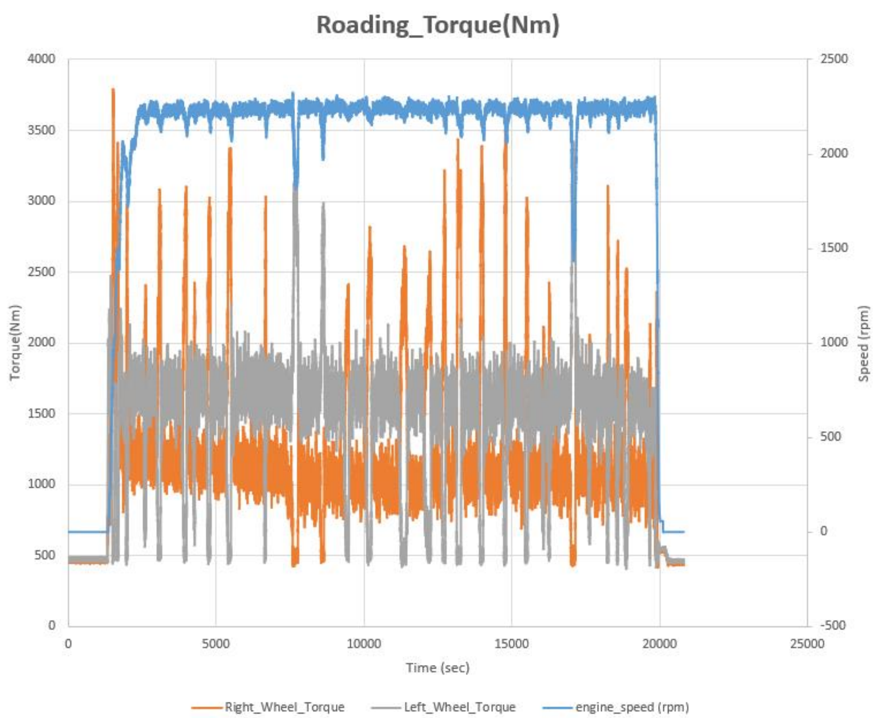

Figure 14: Roading Torque Test Results

5. Result

The future of electric construction machinery appears to be quite promising. The trend towards electrification and advancements in the automotive sector are also pushing developments in construction machinery in this direction. Many construction machinery manufacturers worldwide are conducting electrification efforts and advancements in compact construction machinery.

Positive developments in battery technology are expected to accelerate electrification efforts in other construction machinery products. Factors triggering the electrification process can be listed as follows:

Environmental Awareness: Electric construction machinery has less environmental impact compared to traditional internal combustion engines. By using a cleaner energy source, they reduce carbon dioxide emissions and improve air quality. Additionally, they have lower noise levels, contributing to the reduction of air pollution and noise in urban areas, thereby enhancing environmental sustainability.

Cost Reduction: Electric construction machinery may have lower operating costs compared to traditional machinery. Electricity is generally cheaper and more stable than internal combustion engines. Moreover, maintenance costs and fuel consumption can be reduced.

Technological Advancements: Electric construction machinery can benefit from rapidly evolving technological advancements. Advanced battery technology offers longer operating hours and faster charging capabilities. Additionally, smart technologies such as automatic functions and data analysis can enhance the efficiency of electric construction machinery.

Regulatory Pressures: Many countries are increasing demand for electric construction machinery by tightening environmental regulations and emission standards. This encourages businesses and the construction sector to adopt electric machinery.

However, the full adaption of electric construction machinery may face some challenges. These include high initial costs, infrastructure deficiencies (such as charging stations), and limited operating hours in some applications. Nevertheless, with technological and industrial developments, it is expected that these challenges will diminish over time.

6. Discussion and Conclusion

Determining the most suitable motor for the traction system in a mini backhoe loader machine requires consideration of several factors. Generally, brushless DC motors, asynchronous motors, and permanent magnet synchronous motors are commonly preferred among the electric motors used in these types of machines.

Brushless DC motors can provide high torque at low speeds and have suitable torque-speed characteristics. However, they have disadvantages such as large size, low efficiency, and costly maintenance, which has led to a decreased preference for them.

Asynchronous motors have advantages such as reliability, low maintenance requirements, and low cost. These motors are suitable for applications requiring high torque and are generally preferred in industrial machinery.

Permanent magnet synchronous (PMSM) motors offer high efficiency, reliability, and high performance. These motors can operate at full torque at low speeds and have a wide range of applications.

To determine which motor is more appropriate for the traction system in a mini backhoe loader machine, the functional requirements, performance expectations, cost factors, and usage conditions of the machine should be taken into account. Evaluating these factors and conducting appropriate engineering analysis will ensure the selection of the most suitable motor.

Engineering analysis is a process used to determine the most suitable motor for the traction system in a mini backhoe loader machine. This analysis involves comparing different motor options by considering various factors. Here are some steps to consider in this analysis:

Determination of Performance Requirements: The traction system's requirements should be determined based on the machine's operating conditions and expectations. This includes factors such as torque, speed, power, and efficiency.

Examination of Motor Options: Different types of motors, such as brushless DC motors, asynchronous motors, and permanent magnet synchronous motors, should be examined, and each motor's advantages and disadvantages should be evaluated to select the most suitable motor for your design.

Performance Comparison: The traction system performance should be evaluated and compared for each motor type. This includes assessing factors such as traction power, torque-speed characteristics, efficiency, and reliability.

Cost Analysis: The cost and maintenance requirements of each motor should be examined, and cost-effectiveness should be evaluated.

Application Suitability: The suitability of each motor for meeting the specified performance requirements and suitability for the application should be assessed. This includes considering the machine's operating environment and conditions.

Decision Making: Based on the results of these analyses, a decision should be made to select the most appropriate motor. This decision should consider various factors such as performance, cost, and feasibility.
With these factors considered, most suitable motor can be chosen and implemented into the machine.

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