Design and Verification of a Modular Reconfigurable Test Platform for Electric Tractors

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Abstract: Electric tractors (ETs) have attached significant attention in recent years due to the increasingly stringent exhaust emission policies all over the world. However, testing and evaluating all possible architectures and component sizes for ETs would be a time-consuming and expensive task. Establishing a comprehensive test bench that can implement different powertrain architectures as much as possible is thus an important and challenging task. In this study, a novel reconfigurable test platform is proposed according to the analysis results of the powertrain topologies of ETs. These results provide a verification platform to explore powertrain architecture options in future work. To be easily reconstructed under different architectures, the component installation and control system of this test platform was designed based on the modular, reconfigurable concept. To verify the feasibility of the reconfigurable test platform, two powertrain configurations were built based on this test platform framework. The rotary tillage experiments were conducted on these two configurations. The results show that the proposed reconfigurable test bench is reasonably practicable. Moreover, the control precision of the established test bench is demonstrated by comparing the torque results obtained from the experiment with the reference torque values, which indicated that this test bench also has the potential to be adapted to complex farming work scenarios.

Keywords: electric tractor; powertrain topology; reconfigurable test platform; rotary tillage operation

1. Introduction

Traditional tractors with diesel engines emit pollutants, such as nitrogen oxide and particulate matter [1,2]. To lower the levels of toxic exhaust, many manufacturers of agricultural equipment and researchers around the world have devoted considerable resources for developing electric tractors (ETs) to make them more environmental-friendly and energy-efficient [3].

Similar to electric vehicles, ETs can be divided into two main categories: hybrid electric tractors (HETs) and battery electric tractors (BETs). The HET uses two energy sources to propel the tractor. At present, one type of energy source is an engine supplied by fuel, and the other is a battery plus electric motor drive. In hybrid electric tractors, there are three configurations. The first is a series hybrid, where the engine provides electric power to the electric motor(s) driving the wheels and agricultural equipment, featuring an indirect mechanical connection with the propelling wheels and the power takeoff (PTO) shaft. However, it remains to be determined if this configuration can allow battery recharge from the electric grid and offer a significant range in the purely electric mode; this type of model is called a plug-in hybrid. Here, we regard the plug-in hybrid as a special type of series hybrid. The second is a parallel hybrid, where the engine and the electric motor(s) are mechanically connected with a mechanical coupling device (e.g., a fixed-gear set and a planetary gear set), allowing the components to directly supply their torque to the driving wheels or PTO shaft. The third is a series–parallel hybrid, which combines the series and parallel hybrid configurations into one package and allows one to change the powertrain configuration from series to parallel via the engagement or disengagement
of one or two clutches, and vice versa. BETs are propelled only by their onboard electric motor(s), which are powered by the battery (recharged from the power grid). According to the number of drive motors, BETs can be classified into three categories: (i) single-motor drive, (ii) dual-motor drive, and (iii) four-motor drive (called all-wheel-drive).

In recent years, scholars have investigated the powertrain configurations of ETs by building test benches or fabricating prototypes. For a BET with the single-motor drive system, Zhu et al. [4–6] studied the drive force and transmission efficiency characteristics of a mini tractor with a rated power of 5 kW by developing a BET test bench composed of a series direct current (DC) motor, a magnetic powder brake, and a measurement control system. To study the electric energy consumption of tractors used in a greenhouse, a battery–electric tractor prototype with a single-motor drive system was fabricated and studied via a performance trial in [7]. To research the characteristics of small and medium-sized tractors used in hilly and mountainous areas, Chen et al. [8] proposed a test platform with a three-axis direct-connected electric drive system to conduct experiments, including tests of the external characteristics transmission efficiency, noise, and reliability. Test benches and prototypes of single-motor drive systems for tractors can also be found in [9–12] and allow one to study the electric efficiency characteristics under different farming operations.

Furthermore, each configuration has variable architectures of the powertrain in terms of the inclusion of hybrid electric tractors and BETs in multi-motor drive powertrains. For hybrid electric powertrains, Deng et al. [13–15] proposed a coupling device suitable for the requirements of farming operations, using the concept of a power-split from parallel hybrid electric vehicles as a reference to design a parallel hybrid tractor test bench to verify the performance of the coupling device. Next, a test bench featuring a series–parallel hybrid electric powertrain architecture, where the engine distributes power to the generator and the PTO shaft through the power-split device, was established in [16] to study the dynamic performance of this architecture through the traction experiment. Using BETs with multi-motor drive powertrains, Kim et al. [17] designed a powertrain for a 78 kW all-wheel-drive BET prototype to analyze the reduction gear ratio under actual agricultural working and driving conditions. Zhou et al. [18] established a four-wheel independent driving electric tractor test bench to research the torque distribution of BETs under the working conditions of the traction operation. Recently, BETs with dual-motor drive powertrains have become increasingly attractive to manufacturers and researchers. In 2017, agricultural equipment manufacturer John Deere released the first fully public BET prototype called sustainable energy supply for agricultural machinery. This prototype was equipped with two electric motors, one of which was used to operate the drivetrain, while the other was used for the PTO and auxiliary systems. If required, both motors can work together to supply full power. In other words, the powertrain architecture of this prototype can be a dual-motor independent drive or a dual-motor coupling drive [19,20]. Chen et al. [21,22] designed a tractor test bench with a dual-motor coupling powertrain to verify the optimality of the matched parameters obtained from the particle swarm optimization algorithm based on a mixed penalty function. Additionally, based on this test bench, two experiments featuring a constant load and the traction performance were performed to verify the effectiveness of the control strategy and the power distribution ratio [23].

To date, due to complex factors, for example, heavy and complicated farming load conditions, different farming operations, and various powertrain architectures, researchers and manufacturers generally build corresponding test platforms or prototypes to study various powertrain architectures for electric tractors. However, it is time-consuming and costly to establish test benches or prototypes for each powertrain architecture while also considering different farming operations and environments. Therefore, it is necessary to design tools and methodologies for developing a comprehensive test bench that can realize different agricultural works as much as possible.

In this paper, a reconfigurable test bench for an electric tractor was developed according to the analysis of powertrain topologies. Then, to verify the feasibility of the
reconfigurable test platform, we chose two of the powertrain architectures of an electric tractor to implement the rotary tillage experiment. Specifically, a reconfigurable test platform can satisfy the research into different powertrain architectures to the greatest degree possible in addition to the advantages of strong expandability, high-efficiency, and time and cost savings. Second, a series hybrid electric powertrain and a pure electric powertrain were selected to verify the feasibility of the reconfigurable concept for the test bench by carrying out the rotary tillage operation.

This paper is organized as follows: In Section 2, different powertrain topologies of ETs are analyzed. Section 3 introduces in detail a test platform with reconfigurable components and a control system. Next, a series hybrid electric powertrain and a pure electric powertrain were built and tested based on the framework of the platform. The main parameters of the rotary tillage experiment are described in Section 4. Section 5 shows the experimental results under the rotary tillage operation to validate the feasibility of the proposed reconfigurable method and verify the accuracy of the established test bench. Finally, the conclusions are given in Section 5.

2. Powertrain Topologies

A variety of different powertrain topologies can be constructed to investigate the best one for the targeted electric tractors. To depict the powertrain topology more clearly, two assumptions are made in this paper: (i) Rear wheels, as the drive wheels, are connected with the rear axle, and (ii) the technical parameters of the two drives motors are the same.

Figure 1 shows the topologies for seventeen types of powertrains based on the power flow. In Figure 1, a–c is the powertrain topologies of the battery-electric powertrain topologies, d–h are parallel hybrid powertrain topologies, i–k are series hybrid powertrain topologies, and l–q are series–parallel hybrid powertrain topologies. ICE represents an internal combustion engine, GEN represents a generator, DM represents a drive motor, Wheels refers to the two rear drive wheels, and PTO represents a power takeoff shaft.

![Figure 1. Schematic diagram of powertrain topologies for electric tractors. Note: The solid blue lines represent a direct mechanical connection via a pair of gears or reducer, the blue dashed lines represent a power split device, the yellow dashed lines represent a power split-coupling device, and the brown dashed lines represent a power coupling device.](image-url)
According to the analysis results of the powertrain topologies, a reconfigurable test bench is proposed to study all the topologies in Figure 1 as thoroughly as possible in future work. The reconfigurable frameworks of the structure and the control system for the test bench are detailed in the next section.

3. Framework Design of the Test Platform

3.1. Test Platform Configuration

Based on all the topologies in Figure 1, the reconfigurable test platform consists of an internal combustion engine (ICE) system equipped with a diesel engine, an electric machine system equipped with two drive motors (DMs), a load system equipped with three load motors (LMs), a battery pack system, a transmission system, a control and measurement system, and an auxiliary system. Figure 2 presents a general schematic of the test platform.

Figure 2. Schematic framework of the test platform.

Due to the topography and population distribution characteristics of China, small and medium-power tractors are dominant in the tractor market. Therefore, the present platform was designed to meet the development test needs of electric tractors with small and medium-power. More specifically, a diesel engine with a rated power of 36.8 kW was chosen. This engine cannot only propel the load system directly or indirectly but also combine with a generator to operate as a genset that is capable of directly powering an electric powertrain and charging the battery. Drive motor 1 (DM1), and drive motor 2 (DM2) were permanent magnet synchronous machines (PMSMs) with the characteristics of high-power density, high-efficiency, and low-speed with high torque. The rated powers of the two DMs were both 22 kW. The generator (GEN) was a PMSM with a rated power of 30 kW to match the diesel engine’s power. Furthermore, three asynchronous motors (AMs) with the same power (30 kW) were chosen to simulate the load system. One of them was used as the PTO load to transmit the power to the agricultural equipment like a rotary tiller, while the others imitated two rear drive wheels. The transmission system is composed mainly of a gearbox, reducer, drive axle, and power split-coupling device. In this, the power split-coupling device is vital to the architecture of the powertrain system. Moreover, the control and measurement systems are mainly composed of a dSPACE rapid prototype real-time controller and six high-precision torque-speed sensors with six corresponding torque-power instruments. Four torque-speed sensors with ranges of 500 N·m and two torque-speed sensors with ranges of 200 Nm were selected to measure the torque and speed of the electric machines. In addition, to ensure that the experiment would last more than three hours, the test platform was limited to a battery pack with a size of 132 Ah. Lastly, the auxiliary system includes the cooling system and the DC charging pile. In this platform, the controllers of the two DMs and the generator use self-designed liquid cooling systems to cool down. The electric machines (including the two DMs, the generator, and the three
LMs) use their own fans for air cooling. All main technical parameters of the components are displayed in Table 1.

Table 1. Main technical parameters of the components.

| Name          | Parameters                     | Values               | Pcs |
|---------------|--------------------------------|----------------------|-----|
| Diesel engine | Type                           | Four-stroke          | 1   |
|               | Rated power (kW)               | 36.8                 |     |
|               | Rated speed (r/min)            | 2400                 |     |
|               | Idle speed (r/min)             | 750 ± 25             |     |
|               | Maximum torque (N·m)/speed (r/min) | 165/ ≤ 1800     |     |
| Generator     | Type                           | PMSM                 | 1   |
|               | Rated power (kW)               | 30                   |     |
|               | Rated voltage (V)              | 280                  |     |
|               | Rated current (A)              | 66                   |     |
|               | Rated speed (r/min)            | 3000                 |     |
| Drive motor   | Type                           | PMSM                 | 2   |
|               | Rated power (kW)               | 22                   |     |
|               | Rated voltage (V)              | 250                  |     |
|               | Rated torque (N·m)             | 70                   |     |
|               | Rated speed (r/min)            | 3000                 |     |
|               | Maximum power (kW)             | 30                   |     |
| Load motor    | Type                           | AM                   | 3   |
|               | Rated power (kW)               | 30                   |     |
|               | Rated speed (r/min)            | 1500                 |     |
|               | Rated torque (N·m)             | 195                  |     |
|               | Maximum speed (r/min)          | 4500                 |     |
| Battery pack  | Type                           | Ternary lithium-ion  |     |
|               | Rated capacity (Ah)            | 132                  |     |
|               | Nominal voltage (V)            | 318.2                |     |
|               | Operating voltage range (V)    | 258–356.9            | 1   |
|               | Single voltage range (V)       | 2.8–4.15             |     |
|               | State of charge (SOC)          | 15–100               |     |
|               | Operating range (%)            |                      |     |
|               | BOL maximum continuous charging current (A) | 90            |     |
|               | BOL maximum continuous discharging current (A) | 100            |     |
| Torque-speed sensor 1 | Torque range (N·m) | –200–200             | 2   |
|               | Speed range (r/min)            | 0–5000               |     |
|               | Accuracy                       | 0.1% F.S.            |     |
|               | Rated voltage (VDC)            | 24                   |     |
|               | Rated current (mA)             | 300                  |     |
| Torque-speed sensor 2 | Torque range (N·m) | –500–500             | 4   |
|               | Speed range (r/min)            | 0–4000               |     |
|               | Accuracy                       | 0.1% F.S.            |     |
|               | Rated voltage (VDC)            | 24                   |     |
|               | Rated current (mA)             | 300                  |     |
| Differential reducer | Transmission ratio | 22:1                  | 1   |
| Fixed gearbox  | Transmission ratio             | 1:14                 | 2   |

In this test platform, both the hardware and software were designed with a modular, reconfigurable concept. All the mechanical connections between these components are standardized and easy to install and uninstall. Moreover, the platform has enough space to install or replace the power split-coupling devices based on the different architectures of the powertrain system. The control system is also open-source and easy to expand and
can be implemented in real time. Further, the measurement data acquisition system is safe, reliable, and stable. To reduce the energy consumption of the platform, the power generated by the regenerative braking of the three load electric machines is fed back to the power grid through a grid-connected inverter. In the following subsections, the reconfigurable framework of the control and measurement system for the test bench is described first. Then, the host control framework design and communication protocol are illustrated using a combination of dSPACE and MATLAB/Simulink.

3.2. Control and Measurement System Design

3.2.1. Descriptions of the Control and Measurement System

The control and measurement system for this test platform is mainly composed of a dSPACE product (itself composed of Micro-Auto box II hardware, Controldesk software, and a 24 V power supplier), signal connectors (cable, CAN-High, and CAN-Low), subsystem controller units, sensor receivers, and a laptop, as shown in Figure 3. The dSPACE Micro-Auto box II, which is the platform master controller, first reads and converts the input signals (e.g., torque/speed mode control command, forward speed, field load, and PTO torque/speed) from the Controldesk software via a network cable. Second, the device sends commands to the subsystem controller units along with feedback status information (e.g., battery SOC, battery current/voltage, battery temperature, DM speed/torque, engine speed, generator charging current, and generator temperature) through a controller area network (CAN) hub, thereby running and monitoring the external devices (e.g., engine, generator, DM, and battery). All these modules are progressively cascaded and work together to implement the operation of the entire bench. In addition, a communication protocol is vital to set up in the control system and generally will not be changed once established. The definitions for the communication protocol of the input/output interfaces between the master controller and subsystem controllers are discussed in the next section.

Figure 3. The structure of the control and measurement system for the test platform.

3.2.2. Communication Protocol

CAN is attractive to the automotive and automation industries due to its simplicity, reliability, low-cost, and high-performance. More important, CAN offers a serial bus communications protocol between actuators, controllers, sensors, and other nodes in real time and is known for its strong anti-electromagnetic interference and anti-noise interference abilities [24]. Therefore, in this test platform, the CAN bus protocol was selected as the communication mode for each subsystem controller and measurement
system. All commands from the Controldesk are sent to the subsystem controllers and measurement system, which returns the signals and records the data through the CAN bus. The input/output interfaces of each subsystem controller need to be defined by the CAN protocol. The control system is composed of an engine electronic control unit, a generator controller, two drive motor controllers, two load motor controllers, a PTO motor controller, and a battery management system (BMS). Notably, the communication mode of torque-speed sensors is usually RS232/485. Therefore, an ST51 single-chip microcomputer was designed for the CAN communication conversion interface of the measurement system for transmitting the commands and receiving the messages.

There is a total of six independent real-time interfaces (RTI) CAN channels in the control and measurement system for this test platform. Specifically, CAN1 is the CAN communication channel of the three load motor controllers, including two load motor controllers and one PTO motor controller; CAN2 is the CAN communication channel of the engine electronic control unit and the generator controller; CAN3 is the CAN communication channel of the six torque-speed sensors of the measurement system; CAN4 is the CAN communication channel of the BMS; and CAN5 and CAN6 are the CAN communication channels of the two drive motor controllers, respectively. The configuration of each RTI CAN channel was set up based on the ID address and the message composition (including the transmitted message and the received message) of their controllers.

3.2.3. Host Control Framework Design

To describe the control system design, the platform master controller must first be described. The dSPACE product is generally used for hardware-in-the-loop tests in automotive development [25]. However, in this paper, this product is taken as a rapid prototyping real-time control system to control the subsystem controller units and to run the whole equipment on the tractor test platform.

The Controldesk software and MATLAB software were installed on the laptop. Specifically, MATLAB/Simulink provides a compilation environment for the control strategy model and generates the target code, which is loaded into the Controldesk through the RTI tool of dSPACE. Then, the Controldesk (a user interface) is used to run the entire platform online, while real-time parsing of CAN messages, as well as data recording, are achieved on the computer by means of an ethernet cable during the system’s operation. We also designed two switch buttons on the Controldesk interface via the code generated by Simulink to allow one to switch between manual/automatic input, the speed/torque control modes. Other switch buttons, such as those for switching between different powertrain configurations and switching between energy management control strategies (e.g., Rule-based control strategy, Dynamic Programming, Equivalent Consumption Minimization Strategy, Model Predictive Control, etc.); will be established in future work.

In addition, a modular design concept was also used in the construction of the control system to facilitate the control strategy research of different powertrain architectures. The main procedure is as follows:

Step 1: Determine the target powertrain architecture;
Step 2: Design the logical control strategies using MATLAB/Simulink;
Step 3: Generate the file code with the suffix of “.sdf” from the established Simulink model via the “build model” button of the RTI tool;
Step 4: Load the “.sdf” file into the Controldesk and refresh the configuration;
Step 5: Go online to run the equipment of the test platform and measure and record the data in real time.

The design process of a specific example is given in Figure 4.

As described above, it is flexible to change the logical control strategy in MATLAB/Simulink based on the target powertrain architecture. In summary, regardless of the structure or control aspect, the platform can be reconstructed under different powertrain architectures to improve the utilization rate of the test bench and save time and financial costs. In the next section, a case study is used to demonstrate the application of the test platform.
Define CAN protocol
Determine architecture
Design optimal control strategy in Simulink
Generate code file
Load code file into Controldesk
Go online and record data

Dual-motor independent driven architecture as a example:

| Mode | DM1 | PTO | DM2 | LM | LM |
|------|-----|-----|-----|----|----|
| 1    | ●   | ●   | ●   | ●  | ●  |
| 2    | ●   | ●   | ●   | ●  | ○  |
| 3    | ●   | ●   | ●   | ○  | ●  |
| 4    | ●   | ●   | ●   | ○  | ○  |
| 5    | ○   | ○   | ○   | ○  | ●  |
| 6    | ○   | ○   | ○   | ○  | ○  |
| 7    | ○   | ○   | ○   | ○  | ○  |
| 8    | ○   | ○   | ○   | ○  | ○  |

Note: ● represents torque control ○ represents speed control

1. Rule-based control
2. Dynamic programming
3. Model predictive control
4. Stochastic dynamic programming

Figure 4. The control modeling flow chart.

4. Case Study

In this section, two powertrain configurations (Figure 1b,j) were used to demonstrate the specific implementation of the platform by elaborating on the powertrain architecture and control system. As reported in [22,23], John Deere first released a BET prototype with two DMs that can realize independent drive. Specifically, one of the motors propelled the drivetrain, while the other supplied for the PTO shaft. This is one of the reasons we considered a dual-motor independent drive architecture first. Another reason is that this design simplifies the drivetrain of the tractor and makes multi-gear transmission unnecessary. Second, to illustrate the hybrid part of the test platform, a series hybrid configuration is used due to its prominent advantages in the mechanical decoupling among an engine with drive wheels and a PTO shaft. Eventually, a series hybrid electric tractor with a dual-motor independent drive system structure is taken as an example, which can realize the three configurations in Figure 1: (i) BET with a single-motor drive system (see Figure 1a without PTO); (ii) BET with a dual-motor independent drive system (see Figure 1b); and (iii) BET with a series hybrid drive system (see Figure 1j), thereby verifying
the reconfigurability of the test platform.

4.1. Powertrain Architecture

The series hybrid electric tractor with a dual-motor independent drive system was built based on the framework of the test platform (Figure 2). This system is mainly composed of a genset, permanent magnet synchronous drive motors, asynchronous load motors, a battery pack, a transmission (e.g., a drive axle and speed-up boxes), a grid-connected inverter, torque-speed sensors, and a control system (dSPACE rapid prototype real-time control system), as shown in Figure 5a.

Figure 5. The test platform for a series hybrid electric tractor with a dual-motor-independent-driven powertrain: (a) structural scheme of the series hybrid electric tractor of the test platform; (b) photographs of the reconfiguration test platform; (1) battery pack; (2) communication converter; (3) operating console; (4) laptop; (5) control system of the drive motor 1; (6) control system of the drive motor 2; (7) right load motor; (8) right raising speed gearbox; (9) drive axle; (10) left raising speed gearbox; (11) left load motor; (12) generator control system; (13) generator; (14) exhaust pipe; (15) grid-connected inverter; (16) charging pile; (17) drive motor 2; (18) drive motor 1; (19) PTO motor; (20) lead–acid battery; (21) engine controller; (22) diesel engine. Note: torque-speed sensors are inside of the yellow covers.

In this architecture, the genset comprises a diesel engine, a generator, and a torque-speed sensor 1 with a range of 200 Nm. The diesel engine subsystem provides electric power to both the battery and the DMs. Drive motor 1 (DM1) is connected to the PTO motor via a torque-speed sensor 2 to simulate the operation of the agricultural equipment (such as the rotary tillage implement), which must be powered by the PTO shaft; drive
motor 2 (DM2) propels the two LMs to simulate the tractor’s forward movement by connecting to the drive axle through a coupling and a torque-speed sensor 1. The two LMs are connected to the two output shafts of the drive axle through their respective speed-up boxes, torque-speed sensor 2 with a range of 500 N·m, and couplings. Figure 5b illustrates the physical layout of the test platform of the series hybrid electric tractor with a dual-motor independent drive system.

4.2. Control Strategy and Simulink Model

As mentioned in Section 3.2, it is easy to realize reconfigurable control; we need only design corresponding logical control strategies based on the series hybrid electric powertrain architecture in Simulink and implement those strategies following the steps in Figure 4. The Simulink model for this architecture for the test bench system, based on a modular design, is displayed in Figure 6. As can be seen in the figure, the model is divided into three logical sub-models: Load_Drive_Motor, Engine_Generator_Battery, and Torque-Speed Sensor.

![Figure 6](image)

Figure 6. The control model framework of the series hybrid powertrain used in electric tractors.

Figure 7a shows the logical control relationship between the drive motors and the load motors. The three orange blocks represent the logical models of the two load motors and the PTO motor, and the two green blocks represent the logical models of the two drive motors of motor 1 and motor 2. Similarly, Figure 7b shows the logical control relationship among the engine, the generator, and the battery pack. The yellow block is the logical model of the engine, the cyan block is the logical model of the generator, and the dark green block is the logical model of the battery pack. Lastly, Figure 7c shows the logical communication relationship between the six torque-speed sensors of the measurement system and the upper computer (laptop) through the CAN3 channel. It should be noted that five of the six torque-speed sensors are currently used, as depicted in Figure 5, while the remaining one also has been reserved as a development interface to provide a test platform for research on different architectures (such as the dual-motor coupling structure) of electric tractors.

In addition, due to its modular design, the designed Simulink model can also be used to study BET with a single-motor drive structure (without PTO) or a dual-motor drive independent structure.

4.3. Test Contents

To verify the feasibility and rationality of the reconfigurable test bench, two configurations were carried out under the rotary tillage operation. One is the BET with a dual-motor independent drive system (see Figure 1b), while the other is the BET with a series hybrid drive system (see Figure 1j).

Since the two DMs and the three LMs can be implemented via both the torque control method and the speed control method, there are different possible combinations of control methods for the DMs and the corresponding LMs. In this paper, motor 2 was implemented via the torque control method, and the two corresponding LMs were controlled by the speed control method to simulate the constant forward speed of the tractor. For the purpose
of simulating the rotary tillage operation, the speed control method was applied to motor 1, while the torque control method was applied to the PTO load motor.

Figure 7. Simulink models of the control and measurement system: (a) electric drive model; (b) genset and battery model; and (c) measurement system model.
In farming operations, the forward speed of the tractor is usually required to operate at a relatively stable. Thus, we used a constant forward speed of 2.4 km/h to implement the rotary tillage experiment. Although the PTO shaft speed is generally 540/1100 rpm, the speed of 540 rpm was chosen due to being more often used in small and medium-power tractors. The primary setting parameter values of the test scenario are listed in Table 2. According to Table 2 and the technical parameters of the test bench, the torque value of motor 2 was 14 N·m, the speed values of the two LMs were both 225 rpm, and the speed value of motor 1 was 540 rpm. These values were directly entered into the Controldesk interface via the laptop. However, the rotary resistance forced by soil is random. Thus, we established databases (such as a plowing torque database, a rotary tillage torque database, etc.) of duty cycles composed of data collected by conducting different farming operations in the real field and wrote them into the program to imitate the tillage resistance torque. Figure 8 shows the PTO reference torque imposed on the PTO motor when the test platform simulates rotary tillage operations. This torque cycle is composed of a set of data with values of 31~64 Nm from the rotary tillage torque database. The rotary tillage torque data were obtained from the study conducted in [26] and processed in this paper via smoothing with a five-point cubic polynomial function and interpolation. All experimental data were exported in the “.mat” file format for further analysis.

Table 2. Primary setting parameter values of the test scenario.

| Parameters                  | Values | Units |
|-----------------------------|--------|-------|
| Tractor mass                | 3000   | kg    |
| Driving wheel radius        | 0.5    | m     |
| Forward speed               | 2.4    | km/h  |
| PTO motor speed             | 540    | rpm   |
| Engine working speed        | 1600   | rpm   |
| Charging current            | 15     | A     |

Figure 8. The curve of the power takeoff (PTO) reference torque cycles.

4.4. Results and Discussion

Before 160 s, the test platform simulated a pure electric tractor with a dual-motor independent drive architecture under rotary tillage operations. At 75 s, the PTO motor was provided the reference torque to simulate the resistance torque of the rotary blade shaft.
After 160 s, the test platform simulated the series hybrid electric tractor under rotary tillage operation, and the genset began to charge the battery at 225 s.

The experimental results under the rotary tillage operation are illustrated in Figures 9 and 10. The curves of the torque and speed for each electric machine (e.g., the two LMs, the PTO motor, and the DMs) are displayed in Figure 9. What needs to be explained here is that the result of DM1 is the same as the PTO motor, which is not shown in Figure 9. This is because DM1 and the PTO motor are fixed directly to each other without a reducer (this is a limitation of this study and will be fixed in future work).

As can be clearly seen in Figure 9a, whether in the purely electric mode or the series hybrid mode, the torque of DM2 and the two LMs responded almost simultaneously, and the control precision of the PTO motor and DM1 remained excellent compared to the reference torque cycle, which all indicates that the control system for this test platform has a good control effect. In addition, in the series hybrid mode, the genset received a constant charging current control command. The genset torque quickly reached a particular value, started to decrease slowly, and finally tended to fluctuate in a stable range, as shown by the green curve (Figure 9a). This may have occurred because the generator cooling system was not run before the genset worked for about 25 s, but the temperature of the genset system kept rising, which led to an increase in the thermal energy of the system. To generate a constant charging current value, the engine was forced to provide a larger torque. When the cooling system started to work, the temperature of the genset system gradually cooled down, and the thermal energy decreased to a stable range. This is why the output torque of the engine slowly decreased and tended toward a certain range. The operating state of the genset also became gradually stable, further indicating that the platform can operate normally.

As shown in Figure 9b, the speed response time of the DM2 was faster than that of the two LMs. The same phenomenon occurred in the DM1 and the PTO motor due to the motor characteristics of PMSMs and AMs. However, the speed response time between the two LMs was not the same. Specifically, the response speed of the right load motor was less than that of the left load motor. This was caused by the different frictional resistance of the mechanical connection between the left and right load motors via the drive axle differential. Moreover, the engine speed increased from idle speed to the set value of 1600 r/min, and the speed fluctuation range of the genset was 1590 to 1606 r/min. Further, the maximum relative error compared to the set value was approximately 0.625%. The speed fluctuation of motor 2 was 354–355 r/min, and the maximum relative error with a theoretical value of 353.6 r/min was approximately 0.396%. The left load motor speed fluctuation was 223–227 r/min, and for the right motor, the fluctuation was 222–225 r/min. The maximum relative errors with a theoretical value of 353.6 r/min were approximately 0.889% and 1.333%. The PTO motor was run using variable torque, which made the speed fluctuation larger. The speed fluctuation range was 529–550 r/min, and the maximum relative error from the set value of 550 r/min was approximately 2.037%. All these values are within the allowable range of error for the measurement and control system.

Figure 10 shows the changes in the battery voltage, SOC, and battery current, as well as the charging current of the genset. Specifically, under the rotary tillage operation, before turning on the genset, the PTO motor operated under variable torque, and the battery current changed regularly with variable torque. Both the battery voltage and SOC decreased over time, as shown in Figure 10a. Moreover, the discharge current range of the battery was −7.5~−16.4 A. It should be pointed out that the negative value of the current was the discharging state, and vice versa. When genset began functioning at a set charging current of 15 A, the battery was in an alternate state of charging and discharging with the current range of −2.1~7.4 A. The battery was charging most of the time, so the voltage value and SOC value of the battery gradually increased, as shown in Figure 10b.
of the mechanical connection between the left and right load motors via the drive axle differential. Moreover, the engine speed increased from idle speed to the set value of 1600 r/min, and the speed fluctuation range of the genset was 1590 to 1606 r/min. Furthermore, the maximum relative error compared to the set value was approximately 0.625%. The speed fluctuation of motor 2 was 354~355 r/min, and the maximum relative error with a theoretical value of 353.6 r/min was approximately 0.396%. The left load motor speed fluctuation was 223~227 r/min, and for the right motor, the fluctuation was 222~225 r/min. The maximum relative errors were approximately 0.889% and 1.333%. The PTO motor was run using variable torque, which made the speed fluctuation larger. The speed fluctuation range was 529~550 r/min, and the maximum relative error from the set value of 550 r/min was approximately 2.037%. All these values are within the allowable range of error for the measurement and control system.

Figure 9. The experimental results under the rotary tillage operation: (a) speed curves; and (b) torque curves.

All these results show that the reconfigurable test platform runs well and that the reconfigurable design of the test platform is feasible, thereby providing a platform for further experimental research on configurations and control strategies, including energy management strategies for electric tractors, in the future.
Figure 10 shows the changes in the battery voltage, SOC, and battery current, as well as the charging current of the genset. Specifically, under the rotary tillage operation, before turning on the genset, the PTO motor operated under variable torque, and the battery current changed regularly with variable torque. Both the battery voltage and SOC decreased over time, as shown in Figure 10a. Moreover, the discharge current range of the battery was $-7.5 \sim -16.4$ A. It should be pointed out that the negative value of the current was the discharging state, and vice versa. When genset began functioning at a set charging current of 15 A, the battery was in an alternate state of charging and discharging with the current range of $-2.1 \sim 7.4$ A. The battery was charging most of the time, so the voltage value and SOC value of the battery gradually increased, as shown in Figure 10b.

Figure 10. The experimental results of the battery pack characteristic under the rotary tillage operation: (a) battery current and generator-set charging current; and (b) battery voltage and state of charge (SOC).

5. Conclusions and Future Work

In this paper, a reconfigurable and innovative test bench for electric tractors was proposed according to the analysis results of a powertrain topology. A series hybrid electric powertrain was chosen to conduct the rotary tillage experiment on this test bench in terms of pure electric configuration and series hybrid electric configuration. The experimental results validate the feasibility of the reconfigurable test platform. However, future dynamic experiments under real field operations (such as plowing and transportation) are needed to verify the validity of the test bench response.

First, the mechanical framework of this test bench is flexible enough to be extensively applied to other test benches of different powertrain architectures. Second, the modular concept of control modeling was described in detail to achieve various control strategies that can be used for the initial design of on-road and off-road vehicle test benches, thereby shortening the platform construction period.
Ultimately, this research focused on the development of a test platform. The tools and methodologies for developing the test bench presented in this paper are general and can be extended to other engineering applications, which are valuable and helpful for engineers how to develop similar test benches.

**Author Contributions:** Conceptualization, Z.W. and J.Z.; methodology, Z.W.; software, Z.W. and X.W.; validation, Z.W., I.i.S. and J.Z.; investigation, Z.W. and X.W.; resources, J.Z.; data curation, Z.W. and X.W.; writing—original draft preparation, Z.W.; writing—review and editing, Z.W. and I.i.S.; project administration, J.Z.; funding acquisition, J.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Key Technologies Research and Development Program of China, grant number (2016YFD0701003), Jiangsu Province Key Technologies Research and Development Program, grant number (BE2017370), and Graduate Research and Innovation Projects of Jiangsu Province, grant number (KYCX19_0606).

**Data Availability Statement:** Data is contained within the article.

**Acknowledgments:** The authors would like to express their gratitude to the reviewers of the manuscript for their valuable suggestions and comments. We would also like to thank Hangxu Yang from Jinhua Polytechnic for the data curation.

**Conflicts of Interest:** The authors declare no conflict of interest.

**Abbreviations**

- AM: Asynchronous motor
- BET: Battery-electric tractor
- BMS: Battery management system
- CAN: Controller area network
- DC: Direct current
- DM: Drive motor
- ET: Electric tractor
- GEN: Generator
- HET: Hybrid electric tractor
- ICE: Internal combustion engine
- LM: Load motor
- PMSM: Permanent magnet synchronous machine
- PTO: Power takeoff
- RTI: Real-time interface
- SOC: State of charge

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