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Design of a DSP-Based Real-Time Control Device for Railway Vehicle Simulation

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Abstract

A real-time control device for railway vehicle simulation is designed in this study according to the experimental requirements of a railway vehicle electric traction and electric braking system. The device uses the high-speed processing characteristic of DSP and runs on the basis of both DSP and the corresponding experimental platform. The simulation experiment for a different power grade traction system is achieved through control of the device. Full static and dynamic simulation of the operating condition of the train electric traction and braking system is attained in the case of no commissioning.

***Keywords**: DSP, Traction calculation, Simulation running, Real-time control*

1. Introduction

With the acceleration of the high-speed process of China's railway, the electric traction and electric braking system needs an experimental platform that is close to the actual operation environment of the corresponding system, so that the characteristics of the product can be assessed in the research process. Generally, the static test of a development process can be completed in the laboratory, whereas the dynamic test can be completed through commissioning. However, these processes do not only involve along cycle, large workload, and high cost, but they also affect the high-speed development of railways in China [1].

To solve this problem, a real-time control device that simulates running railway vehicles and is applicable to any power and speed grade, as well as its corresponding experimental platform, is designed and developed with DSP as the core technology. This control device and the corresponding experimental platform can simulate train operation whose route and staff load are scheduled. In the actual operation of the train, the traction motor is controlled by the torque mode, whereas in this experimental system, the actual operation of the train traction motor can be simulated through control of the torque of the tested motor. Changes in train speed can be simulated through a control of the rotating speed of the company motor. The operation condition of the electric traction and electric braking system can be simulated by this system, including static and dynamic simulation [2].

2. Hardware Circuit Design of the Control System

The entire system hardware consists of the main circuit, an industrial control computer, a TDSLF2407EA application circuit, a group of Siemens inverters, an IN338 intelligent instrument to measure the torque and rotating speed, and a set of three-phase AC asynchronous motors, as shown in Figure 1.

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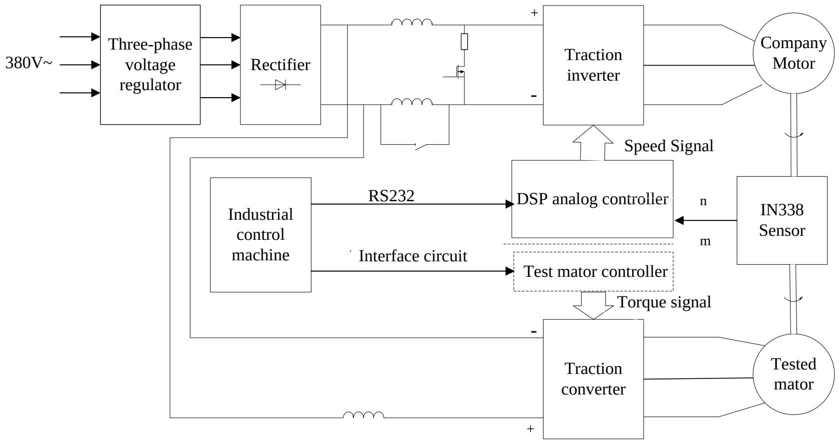

Figure 1. Block Diagram of System Hardware Structure

A three-phase voltage regulator and a three-phase full-bridge rectifier can regulate and rectify 380V AC to 750V DC busbar voltage. A traction inverter controls the company motor through its speed mode, whereas the traction convertor controls the tested motor through the torque mode. The industrial control computer communicates with the DSP simulation running controller via RS232. The system is initialized, including the circuit, train marshalling, and the passenger load factor, through communication with it. The IN338 torque and speed sensor obtains the torque and speed signals and forwards them to the DSP simulation running controller, which then simulates these signals and outputs the results to the traction converter and traction inverter. A speed variation in the company motor of the corresponding power level can be obtained by this closed-loop regulation.

2.1. System Structure of the DSP Controller and the Control Mode of System Operation

1) System structure of the DSP controller

The system structure of the DSP controller includes a power-switching circuit, DAC7625 circuit, crystal oscillation interface circuit, program memory circuit, data memory circuit, PWM drive circuit, communication circuit, and protection circuit, to name a few, as shown in Figure 2.

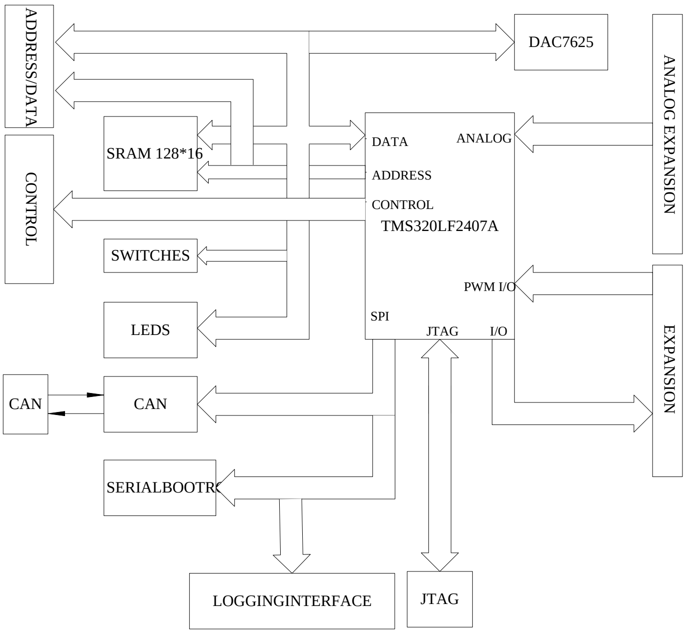

Figure 2. Logic Diagram of DSP Control Board

2) System operation mode

In this experiment, an industrial control computer and a DSP simulation running controller are connected by JTAG interface during the debugging stage. The industrial control computer communicates with the DSP simulation running controller via RS232, and the DSP simulation running controller outputs the processed data in two different ways. First, the D/A conversion module outputs the data to the A/D conversion module of the inverter, and second, the SCI module of the DSP outputs the data to the RS458 serial port of the inverter. Both ways use USS protocol. The DSP simulation running controller sends the signals to the traction inverter connected to the company motor and the converter connected to the tested motor. The company motor is controlled by speed, whereas the tested motor is controlled by the torque to achieve real-time control of the motor torque and speed under the predetermined route, group, and passenger load factor. The system structure of the control circuit is shown in Figure 3. The system is a closed-loop system, and the signals transferred to the motor group are obtained by the sensor, transferred to the DSP simulation running controller, and then passed to the motor group by the traction inverter and converter. The cycle continues until the specified line runs out, and a variation in the company motor speed is reached.

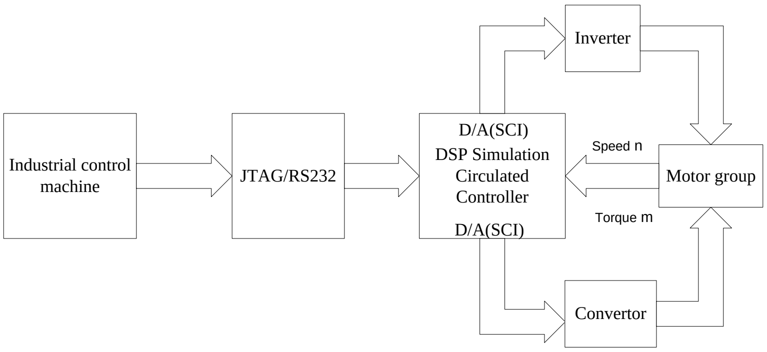

Figure 3. System Frame Chart of the Control Circuit

2.2. Acquisition System of the Experimental Data

In the control system of this experiment, speed and torque signals of the motor are collected by IN338 intelligent digital sensor for measuring torque and speed. Torque and speed signals outputted by IN338 are transferred to DSP's A / D converter after opto-isolator and f/V converter, then A/D1 and A/D2 will complete the collection of the torque and speed signals [3-4]. As shown in Figure 4.

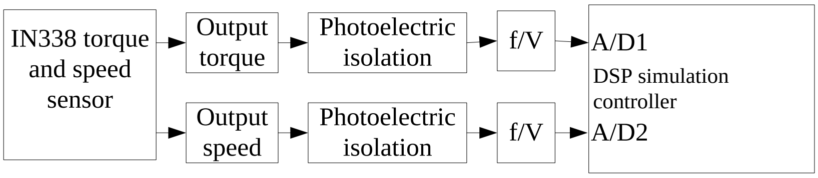

Figure 4. Hardware Chart of DSP Torque and Speed Measuring

2.3. Design of the Signal Preprocessing Circuit

The experiment system uses closed-loop control. After the initial speed and traction are given, the speed and torque signals processed by the DSP simulation running controller are transferred to the inverter group. The voltages of the torque signals transferred to the tested motor by the traction converter range from –10V to +10V, and the voltages of the speed signal transferred to the company motor by the traction inverter range from 0V to +10V [5-7]. Because the reference voltage of the A/D module of TDS2407EA is 3.3V (unipolar), the voltage range of the torque and speed signals acquired by IN338 needs to be adjusted. The level conversion schematic diagram is shown in Figure 5.

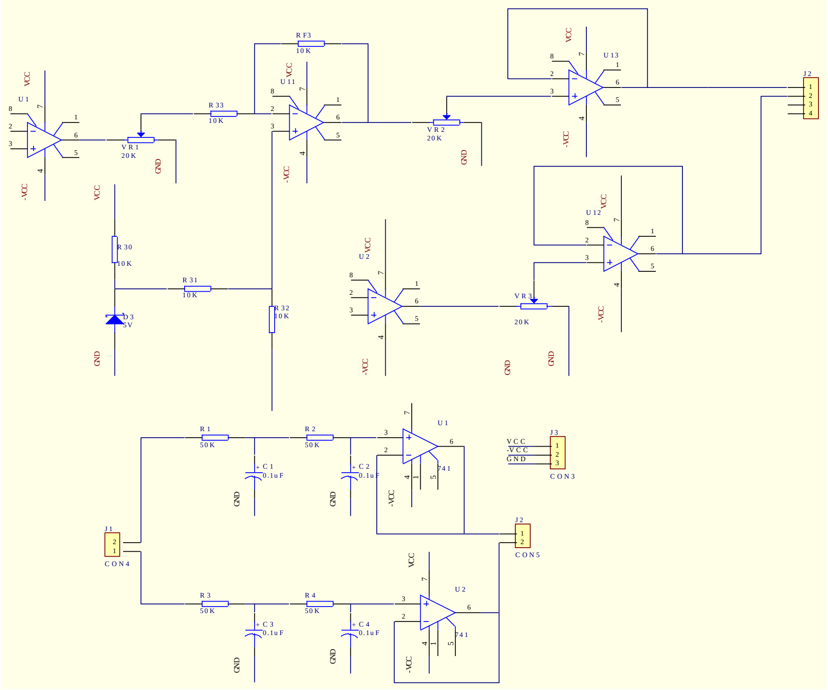

Figure 5. The Level Conversion Schematic Diagram (Input Module)

2.4. Design of the Output Control Circuit

The user board of TDS2407EA is extended with D/A conversion chip DAC7625, which is 4 channeled, 12-bit double buffered, and the output is a DC voltage of 0–2.5V. The A/D module voltage of the traction inverter receiving the speed signal ranges from 0 to 10V, whereas the A/D module voltage of the traction converter receiving the torque signal ranges from –10V to +10V. The speed and torque signal circuit corresponding to the voltage are then designed, as shown in Figure 6. The circuit can transfer voltage and current. When it transfers voltage, the output voltage can be 0V to 10 V and −10V to +10 V; if the current needs to be transferred, the voltage-current converter chip AD694 can transfer voltage to two ways of current, which is 4–20 mA or 0–20 mA.

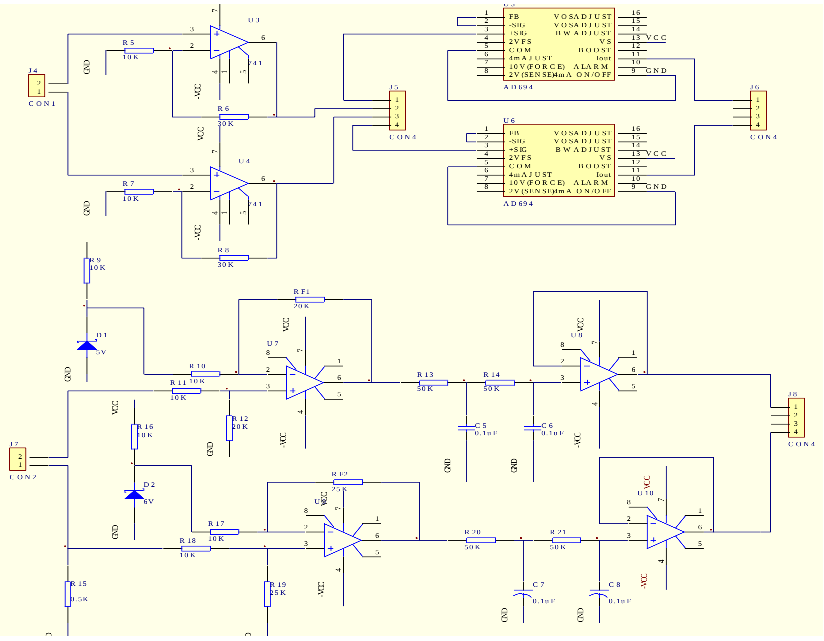

Figure 6. The Level Conversion Schematic Diagram (Output Module)

2.5. Design of the Operating Circuit

In this system, the operating circuit includes an analog circuit of the driver handle position and a switching circuit to simulate the conditions.

1) Design of the analog circuit of the driver handle position

In simulating the control system of railway vehicles running, the driver handle position needs to be simulated to complete the driver’s set for traction and braking position and generate the required control signals. These signals will then be transferred to the traction and braking system. The function of the driver handle position is accomplished with the use of a multiturn potentiometer to change the voltage value, so that a stepless speed or step speed regulation can be achieved, as shown in Figure 7.

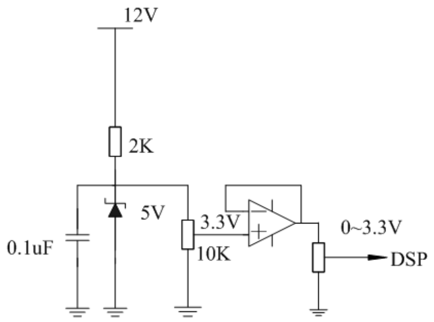

Figure 7. Handle Bit's Simulation (The Multiturn Potentiometer)

The traction and braking handle position are designed in the system, and 0–3.3 V is divided into eight parts. Different voltage ranges correspond to different traction and braking handle positions. During the course of the experiment, the real-time control of the driver handle position for the operating condition is achieved through an adjustment of the output voltage range of the potentiometer.

2) Design of the switching circuit to simulate the operating condition

Because the DSP simulation running controller has a LED and hand switch, these are combined with the software to design the operating condition signals. If switch SW1 is pressed, light DS4, which represents the traction operating condition, will be lighted; if switch SW2 is pressed, light DS5, which represents the braking operating condition, will be lighted; if switch SW3 is pressed, light DS6, which represents the coasting operating condition, will be lighted; if switch SW4 is pressed, light DS7, which represents the stop operating condition, will be lighted. The schematic of the operating condition is shown in Figure 8.

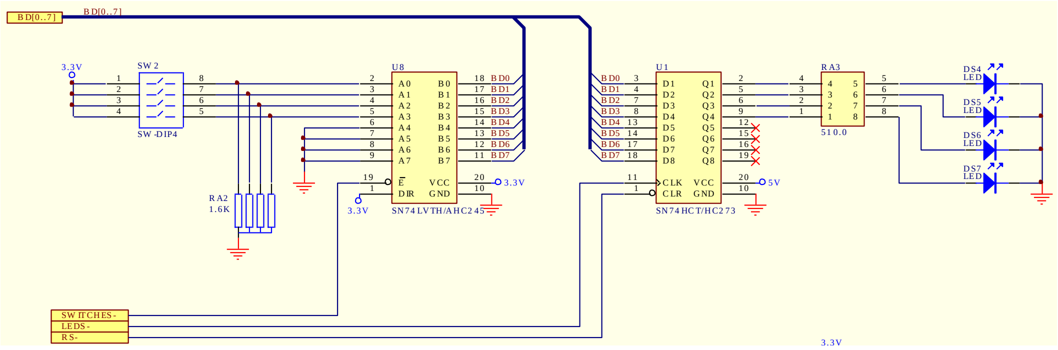

Figure 8. Schematic of Operating Condition Giving

3. Train Simulation Model and Algorithm

3.1. Simulation Running Model

The train motion equation is the central link of train motion theory, the central link is to study the interrelation between traction force (or braking force) , resistance and acceleration (or deceleration) so that the interrelation among train operating speed, operating distance, operating time and tractive tonnage can be find out.

When train is running on the line, there are three operating conditions: traction, coasting, braking [8-9].

If the operating condition is traction, the resultant force acting on the train is:

$$C = F - W_k \ (N) \tag{1}$$

The unit resultant force is:

$$c = \frac{C}{(P+G)g} = f - w_k \quad (N/kN) \tag{2}$$

Where, F is tractive effort at wheel rim (N), W_k is the total resistance (N), P is total weight of the train (t), G is the total weight of the trailer, w_k is unit total resistance, f is unit tractive effort at wheel rim (N).

If the working condition is coasting, traction is zero, the resultant acting on the train is:

$$C = -W_k \ (N) \tag{3}$$

The unit resultant force is:

$$c = \frac{C}{(P+G)g} = -w_k \quad (N/kN) \tag{4}$$

If the working condition is braking, the resultant acting on the train is:

$$C = -(B + W_k) \ (N) \tag{5}$$

The unit resultant force is:

$$c = -(w_k + b) \quad (N/kN) \tag{6}$$

Where, B is train braking force (N), b is unit braking force (N/kN).

Obviously, when $C < 0$, the train will slow down, when $C > 0$, the train will speed up, when $C = 0$, the train will do uniform motion.

The relation among running distance, speed, time and acceleration is shown as(7)and(8).

$$\Delta t = t_2 - t_1 = \frac{v_2 - v_1}{0.2c} \ (\text{min}) \tag{7}$$

$$\Delta s = s_2 - s_1 = \frac{v_2^2 - v_1^2}{24.4c} \ (km) \tag{8}$$

Where, t_1, v_1 and s_1 represent running time before a moment, running speed and running distance respectively. t_2, v_2 and s_2 represent the moment after simulation step Δt, running speed and running distance respectively.

3.2. Simulation Algorithm

The algorithm used in the system simulation is a fourth-order Runge–Kutta method, and the formula is

$$y(k_{k+1}) \cong y_{k+1} = y_k + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{9}$$

Where,

$$k_1 = f(t_k, y_k) \ ; \ k_2 = f(t_k + \frac{h}{2}, y_k + \frac{h}{2}k_1)$$

$$k_3 = f(t_k + \frac{h}{2}, y_k + \frac{h}{2}k_2) \ ; \ k_4 = f(t_k + h, y_k + hk_3)$$

The formula consists of two parts. The first part is the result of a previous step, y_k, which is the speed of the previous moment. The second part is the weighted average of the time step h multiplied by the slope of the each point, which is the weighted average of the running acceleration of each point. When the initial value is known, the speed of the next moment can be determined with Formula (9).

3.3. Simulation Step

When simulation step h is selected, ensuring the computational stability and calculation accuracy is necessary.

When the fourth-order Runge–Kutta method is used, the following empirical formula can be utilized to determine the simulation step:

$$h \le \frac{t_n}{40} \tag{10}$$

Where, t_n is system transient time under the action of step function

Because the train movement is an inertial system whose time constant is large, the simulation step calculated h≤10. The simulation step is limited by a truncation error, so h cannot be too large. The truncation error is proportional to the five power of h to ensure that the calculation accuracy is around 0.5%, which is h = 0.5.

4. Software Design of the Control System

System software is developed in the CCS environment which supports the hybrid programming of C language and assembly language [10-12]. The system software is completed by embedding assembly language in C language.

4.1. Design of the Main Program

First, main program of the control system calls the system initialization program, if runs, judge the working condition, if not, circular wait. The frame of main program is shown in Figure 9.

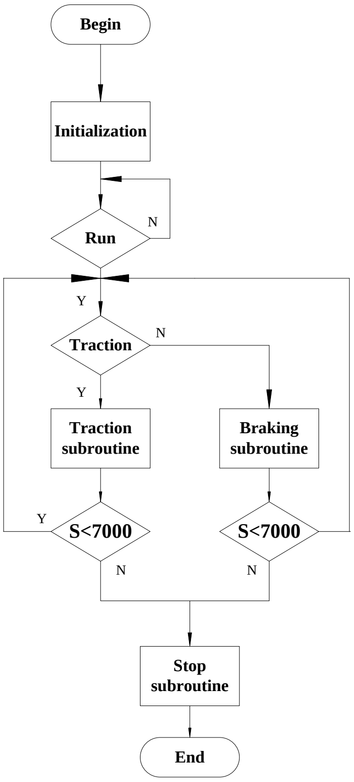

Figure 9. The Frame of Main Program

4.2. System Initialization

The system needs to be initialized before the main program is executed.

System initialization consists of two parts. One is parameter initialization of the control system, which includes setting the traction (braking), number of traction motors, wheel diameter, gear ratio, transmission efficiency, speed, distance, time, and time step, among other factors. The other is initialization of the DSP simulation running controller whose function is to initialize the variable, system clock, status register, external wait, A/D module, and I/O module, among other factors, as shown in Figure 10.

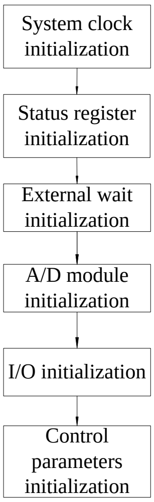

Figure 10. Flow Chart of the DSP Initialization Module

4.3. Speed Analog Control Module

1) Subprogram of the tested motor

At the beginning, the subprogram of the tested motor evaluates the working condition. If it is traction, the analog handle position and input traction characteristic curve are set. If it is braking, the braking characteristic curve is inputted, so that the torque is outputted. If it is neither, the program of the stop working condition is executed. The process is shown in Figure 11.

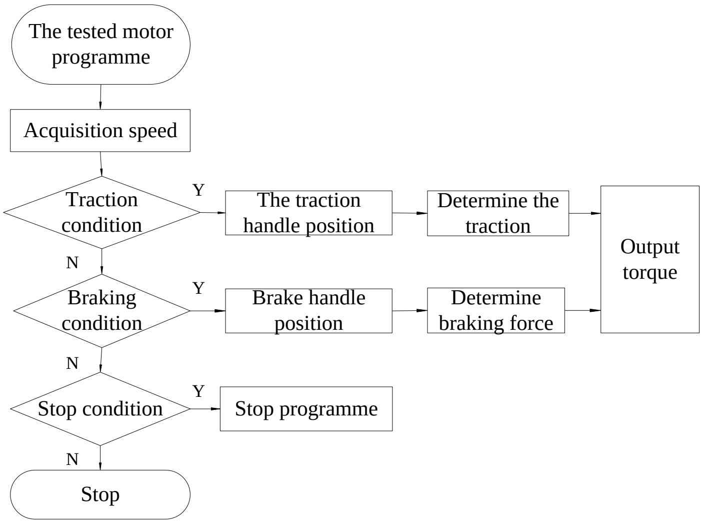

Figure 11. Subprogram Frame of the Tested Motor

2) Subprogram of the company motor

Control program of the company motor is designed to realize the traction calculation , the program flow chart is shown as Figure 12.

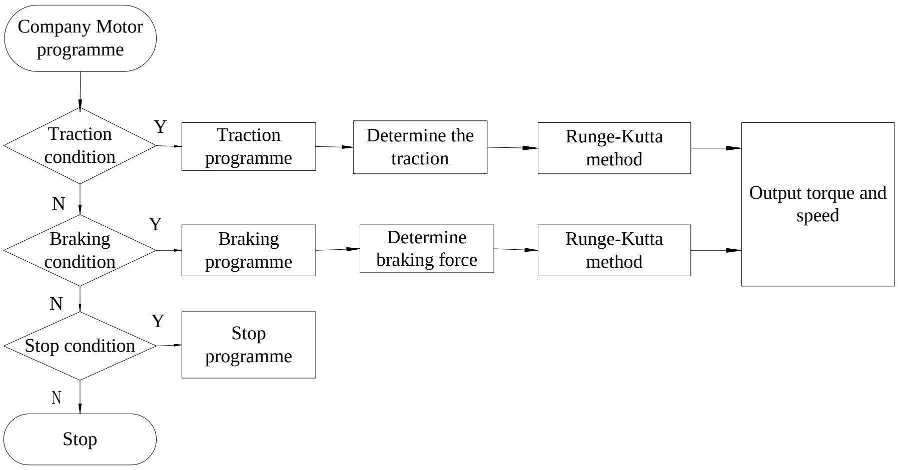

Figure 12. The Accompanied Electromotor Program Frame

4.4. System Collection Module

The system obtains the speed and torque signals through the A/D module of the DSP simulation running controller in real time. The system then outputs these signals, as shown in Figure 13, after they have been processed by the controller.

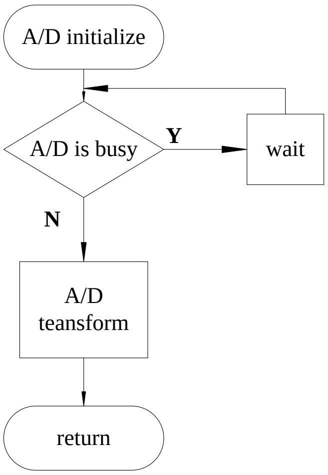

Figure 13. The Frame of System Collection Module

4.5. Design of the System Output Module

The system uses two methods for real-time motor control. One method involves a convertor, which has the function of D/A, to output the analog signal directly and thus control the motor; the output range is 0–2.5 V, which is then converted to −10V to +10V to correspond to the inverter’s AD reception range. The other method involves using a serial interface to output the controlled quantity with an RS232 serial interface of the analog run controller, receive the RS485 serial bus data of the motor monitoring device, and thus realize real-time control, as shown in Figure 14.

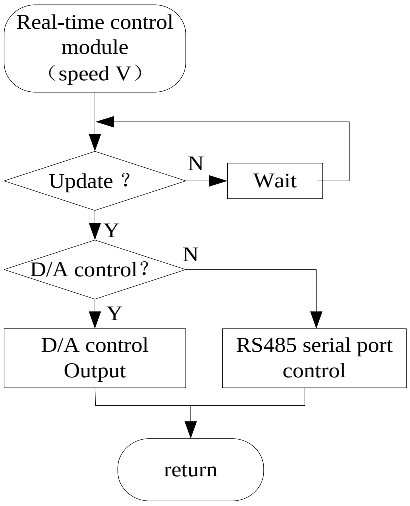

Figure 14. The Frame of System Output Module

4.6. Generality and Scalability of the System Software

The system combines hardware design and software programming to simulate the train operation. With the various factors affecting train operation considered, such as changes in the operation line, traction/braking characteristics, and differences in the test motor, a modular design is used to write software. The train model, marshalling condition, and the parameters involved in the traction/braking characteristic curve can be set in the initialization process. For instance, the program used to achieve basic running resistance of the train is shown as follows:

```
float jz(float v)
{
      float jz=c0+3.6*c1*v+12.96*c2*v*v;
      return(jz);
}
```

When the system initializes, the basic drag coefficients c0, c1, and c2 are initialized through serial port communication between the industrial control computer and the DSP simulation running controller. When changes in the system working environment cause the basic drag coefficient to change, we only need to attach the changed values to c0, c1, and c2. These different parameters ensure that the device is applicable to the real-time operation of the train in different power levels and groups.

5. Experimental Process and Results

In order to achieve the train simulation running, you need to set scheduled route, scheduled load factor, marshalling condition and the driver handle position *etc.* The circuit diagram is shown as Figure 15.

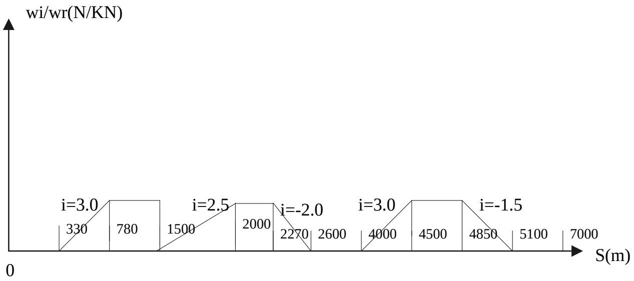

Figure 15. The Circuit Diagram

With the rated power(15kW), wheel diameter(1000mm), and transmission ratio(0.98) of the tested motor in the experiment, the traction curve corresponding to the max traction handle position and the braking curve corresponding to the max braking handle position can be determined. The middle handle position is calculated with the interpolation method.

In the simulation process, some space is opened up in the data storage unit of DSP to store the speed value in real time. Post experiment, the speed curve of the train can be obtained after Matlab processing. This curve is outputted when the traction motor power is 15kW, the rated speed is 1176 r/min, the motor car weight is 11t, the trailer weight is 9t, the passenger load factor is 50%, and the train runs at max traction and braking handle position. The speed curve is shown as Figure 16, and the traction and braking curve is shown as Figure 17.

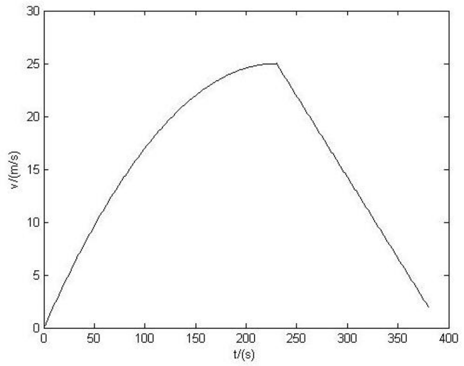

Figure 16. The Speed Curve

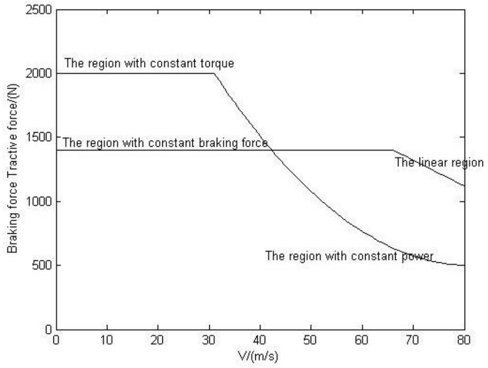

Figure 17. The Traction and Braking Curve

6. Conclusion

A real-time control device is developed to simulate the operation of a railway vehicle. This device can be applied to a traction system that has different power levels. The experiment uses a motor group whose power level is 550V/15kw to complete the dynamic simulation of the running train and verify the reliability of the device. The application described in this study works well during the experiment, and the set goal is achieved.

Acknowledgments

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