HIGH-RENEWABLE MICROGRID FOR RAILWAY POWER CONDITIONER(RPC)

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Abstract

In recent years, the electrification of railways has experienced rapid development and has become an effective means to enhance transportation. However, challenges such as harmonics and negative sequence power quality issues persist. This is mainly because the power supply system of the electrified network operates on a three-phase supply, while the railway traction system is energized through two phases alternatingly. As a result, power imbalances occur at the intersections. This paper proposes a railway power conditioner, which consists of two bidirectional AC/DC converters. It not only allows bidirectional energy flow but also prevents harmonic pollution. Additionally, it provides a stable DC bus voltage for subsequent circuits. Moreover, we also present a method to compensate for railway power using renewable energy sources, giving the system a significant competitive advantage. Experimental results demonstrate that the designed RPC and DC/DC converters efficiently achieve their objectives and exhibit excellent immunity to interference.

Keywords: railway power conditioner, phases, imbalance, AC/DC converters, DC/DC converters

Contents

1. Introduction

1.1 Background and Purpose

Electrified railways offer numerous advantages, such as enhanced safety, improved comfort, increased transportation capacity, and reduced travel time, making them effective solutions for addressing traffic inconveniences. However, as electrified railways have rapidly developed, power quality issues, including harmonics and negative sequence, have become significant concerns. Additionally, challenges have emerged in the traction power supply system, particularly in the effective utilization of regenerative braking energy.

Currently, traction substations charge fees based on a two-part electricity pricing system, and the inefficient utilization of regenerative braking energy can result in higher fees and significant economic impact. Specifically, in practical situations, the external power supply system operates in three phases, while the traction network of electrified railways typically involves only two phases. Randomly selecting two phases from the three-phase power grid leads to power consumption mismatches across the power lines. Therefore, it is necessary to devise a solution to balance the power consumption on each line.

Furthermore, during the operation of electrified railways, the environment is subject to fluctuations, and small disturbances can exist within the system. This necessitates the development of a resilient system capable of mitigating such disturbances. For instance, variations in friction between the train and the ground occur in different areas, and the train may encounter inclines at times. To maintain a uniform velocity, unified traction cannot be simply applied. Additionally, the power supply voltage cannot remain constant, and there will inevitably be some minor vibrations. Ensuring the proper functioning of the train despite changes in the external environment is of paramount importance [1].

In this context, the purpose of this experiment is to address power quality issues and ineffective utilization of regenerative braking energy in electrified railways. We aim to develop a solution that balances power consumption on each line and ensures the system's resilience in the face of disturbances, facilitating the smooth operation of the trains.

1.2 Design Overview

The investment in railway power conditioners has solved these problems very well. Our overall plan is to connect the three phases of the power grid circularly to the traction network at different sections of the railway. In other words, suppose the three phases are phase a, b, and c, and we choose phase (a, b), phase (b, c), and phase (c, a) as input voltage periodically every few kilometers, the power supply grid will be close to balance in the large scale. To balance the power supply on the breakpoint of the traction network where the selected three phases input is changed, a railway power conditioner (RPC, hub of power conversion) is designed to dynamically balance the interphase active power. A microgrid is also connected to the RPC and plays the role of a reservoir. It will absorb extra power or supply backup power during disruption, and it provides an approach to utilize regenerative braking energy to increase energy efficiency, which is the biggest innovation of our project. Control theorems are added to make the traction network stable and improve the quality of the power supply, which is also a big innovation [2].

1.3 Block Diagram

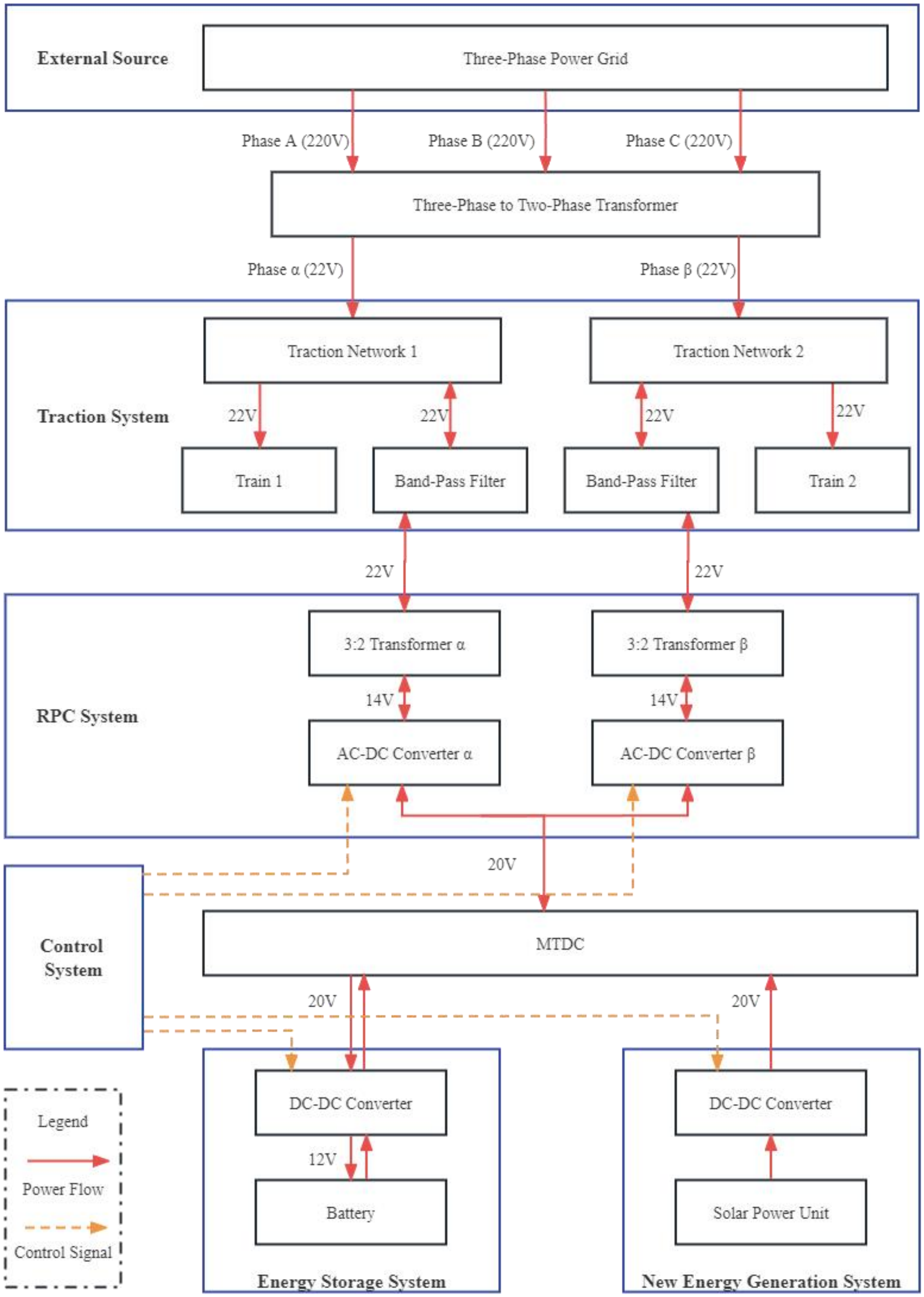


Figure 1: Block Diagram for the whole RPC system

1.4 Subsystem Overview

1.4.1 Traction System

The traction system includes trains, loads, power grids, and transformers. In fact, in this system, we used resistors instead of trains. The three-phase voltage source is the external voltage source that supplies power to the system. Transformers were used to transform external three-phase voltage to two one-phase voltages with a 120°phase difference. We used a safer 220V three-phase power socket instead of using a 110kV/220kV external power grid. What's more, we built a microgrid to drive the train and used power detection to realize the simulation [4].

1.4.2 Railway Power Conditioner (RPC)

The RPC (Railway Power Conditioner) subsystem serves as the central subsystem in this project, as it is responsible for connecting the traction system and MTDC (multi-terminal DC) system. It utilizes transformers and AC/DC converters to handle voltage step-down and phase synchronization tasks, ensuring efficient power transfer and system stability. Specifically, AC-DC converters are directly connected to the transformers located under two trains. The objective of the entire system is to dynamically balance the interphase active power, independently compensate the reactive power of each feeder, and suppress harmonics.

Transformers are utilized in this subsystem to step down the high voltage from the traction network to a lower and safer voltage level that can be easily handled. This step-down process ensures that the voltage level is compatible with the requirements of the system. AC/DC converters are employed in the RPC subsystem to eliminate the phase difference between the two sides of the breakpoint, allowing them to be effectively connected. This conversion process enables the system to achieve smooth and efficient power transfer between the traction system and MTDC system while maintaining synchronization and stability [3].

1.4.3 MTDC (Multi-terminal DC Transmission Control System)

As a bus connecting RPC and coordinating the energy system, MTDC is an indispensable connection hub. It provides a connection to the energy storage systems and energy generation systems. By connecting to energy generation systems like solar panels, we can achieve our objective of making use of sustainable, environmentally friendly energy. Meanwhile, energy storage systems like batteries behave as a reservoir that will absorb excess power from the traction networks and photovoltaic (PV) panels and will provide backup power for the traction networks. With the MTDC subsystem, we can incorporate green energy into our RPC system and store excess energy on the traction network, which improves the energy quality of the external grid.

1.4.4 Control System

The control system is a crucial component of the project, involving the implementation of algorithms to ensure the safe and stable operation of the train. The control system interacts with and influences the RPC subsystem and MTDC system. Initially, an open-loop control strategy will be employed, followed by the design and implementation of a Proportional-Integral-Derivative (PID) closed-loop control approach. Additionally, a data-driven maximum power point tracking (MPPT) control technique will be explored to extract maximum power from the solar panel within a ten-second interval.

The control system will involve the design of control signals for switching functions, which will be executed using an Arduino platform or Digital Signal Processing (DSP). These control signals will enable the opening or closing of specific switches to achieve the desired operation of the converters. The control system will be carefully designed and optimized to ensure the efficient and effective operation of the overall system while maintaining the safety and stability of the train.

2 Design

2.1 Traction System

2.1.1 Overview

To satisfy our requirements and verification of the traction system, we design the traction transformer using two step-down transformers and connected them in V/V type, which means the high-voltage side of the transformer is connected to the three-phase power grid, two sections of the low-voltage side of the transformer are connected to the traction network, and the other end is connected to the return ground line in the form of a common endpoint [5]. In our design, we built two step-down transformers with a coil ratio of 1:10, and their rated power needs to be large enough. The final result is that 220V three-phase electricity is transformed into two single-phase electricity with a phase difference of 120 degrees and a voltage of 30V after passing through these two transformers.

2.1.2 Simulation

To prove the feasibility of our design, we first conducted the simulation on MATLAB. In this section, we need a graph showing an output phase difference of 120 degrees, and by changing the ratio of the primary and secondary coils of the transformers, we can achieve an output voltage of 30V.

We design based on a V/V type connection, and the simulation of the traction transformer is shown in Figure 2. To be more specific, in the simulation, the primary coils of transformers are connected to phase AC and phase BC, and the secondary coils of transformers are connected to GND and the traction network.

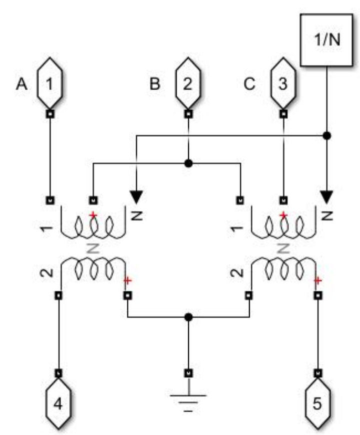


Figure 2: Simulation structure diagram of traction transformer

The result of the simulation is shown in Figure 3 Here we can see that the blue and yellow lines represent two output voltages, and the phase difference between them is measured to be 120 degrees. In addition, after testing, a step-down transformer with a turn ratio of 10:1 between the primary and secondary coils can roughly meet our demand for reducing the voltage to 30V.

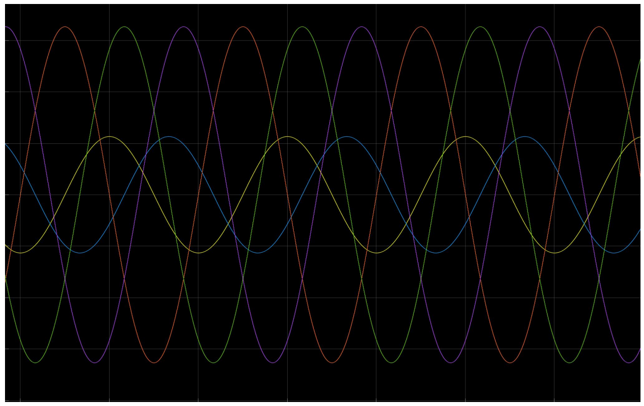


Figure 3: Simulation result of the traction transformer

2.1.3 Actual Design

As for the transformer, which is shown in Figure 4, we used existing materials from the school for production. We selected a U-shaped iron core made of ferrite material and wound the coil with enameled wire. The actual turn ratio of the original and secondary coils is 9.5:1 (this is due to the resistance loss and certain magnetic leakage of the transformer).

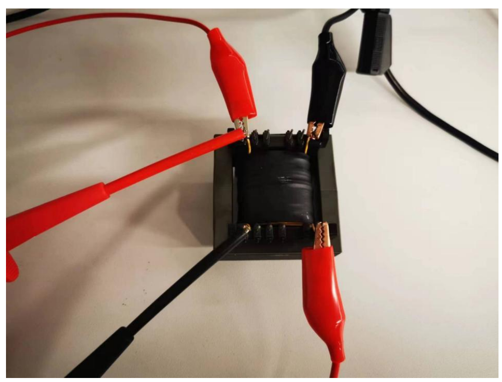


Figure 4: Hardware part of the transformer

For the power supply, we used an adjustable three-phase power supply provided by the laboratory, which is shown in Figure 5.

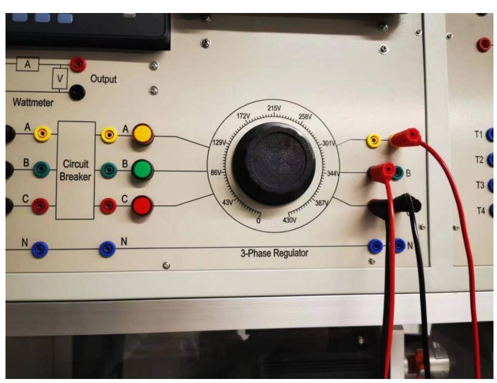


Figure 5: Hardware part of the three-phase power supply

2.2 Railway Power Conditioner (RPC)

2.2.1 Overview

To satisfy our requirements and Verification of the railway power conditioner, we design the main RPC structure using two bidirectional AC/DC converters. We design it in a clever way of connecting AC/DC converters back-to-back. Specifically, AC-DC converters are directly connected to the transformers located in the traction system. The objective of the entire system is to dynamically balance the interphase active power and to control the quality of the grid side current to prevent harmonic pollution. At the same time, it also needs to provide a relatively stable DC bus voltage for the subsequent circuit.

2.2.2 Simulation

We first conduct a simulation on MATLAB to ensure that our design drawings can be achieved as desired and to identify components that are suitable for the specifications.

We design based on the Visual Aid, and the simulation model of RPC is shown in Figure 6. In addition to the two main bidirectional AC/DC converters, the capacitance and inductance in the subsystem are used to store part of the energy during the equilibration.

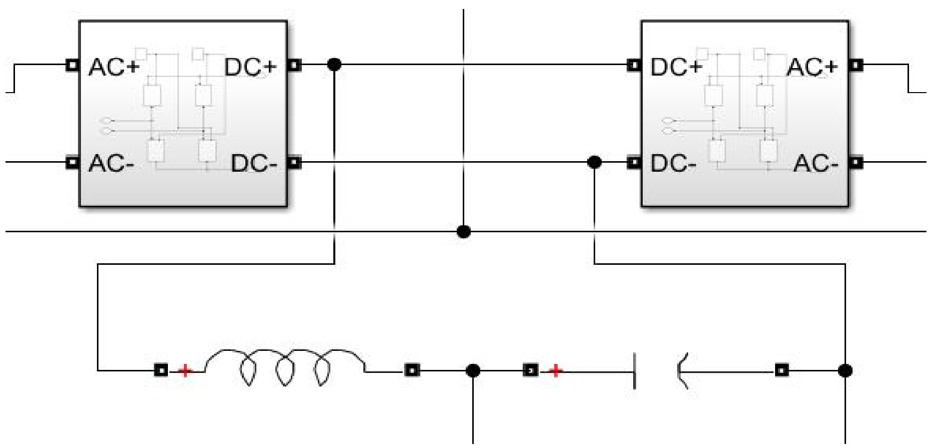


Figure 6: Simulation structure diagram of RPC

For the simulation model of two bidirectional AC/DC converters, we use four IGBTs which behave as switches to form a full-bridge AC-DC converter. As shown in Figure 7. For signal control of IGBTs, I used sinusoidal pulse width modulation (SPWM). When the converter is in rectifier mode, IGBT3 and IGBT4 are disconnected and conducted every half voltage cycle. At the same time, they must satisfy non-simultaneous conduction. When the circuit is in reverse energy supply mode, four switch tubes form a buck circuit in the positive and negative half cycles of the power grid, transferring energy from the DC side to the traction system side.

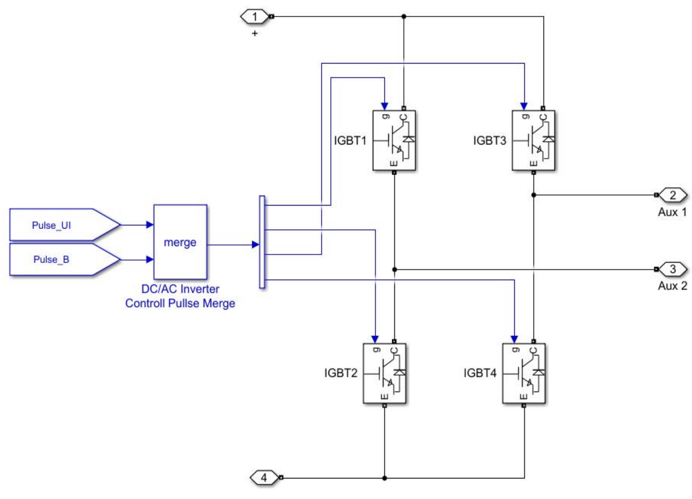


Figure 7: Simulation structure diagram of RPC

2.2.3 Actual Design

When implementing simulation on hardware, we may be limited by some practical conditions and partially use other electronic devices to replace the components in the simulation. But the overall function and effect are the same. The hardware part of RPC is shown in Figure 8. It is composed of one PCB board, two inductors, one STM32, two current-type voltage sensors, and two transformers. Its goal is to achieve power transmission. It has two symmetric AC interfaces and one DC interface.

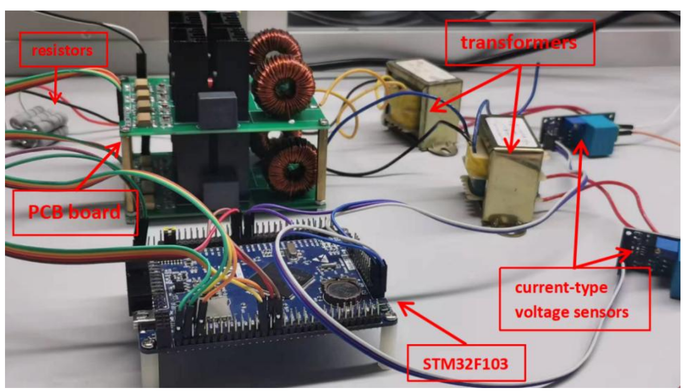


Figure 8: Hardware part of RPC

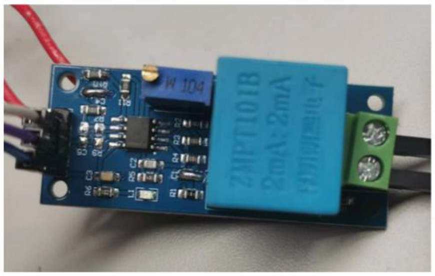
PCB: The schematic diagram of the PCB is attached in the final Appendix. Different from what we simulated on MATLAB, eight MOSFETs are used to form two identical AC/DC converters. The upper and lower boards of the PCB in Figure 9 are the same, and they are connected by six parallel 500-ohm gray resistors. The six parallel 500-ohm resistors are the load on the DC end of RPC, and the wires extending from them can be connected to the bus of the MTDC subsystem. After experimental verification, the voltage at both ends of the load has always been a constant 20V DC voltage. This meets the requirements of "The RPC system outputs a stable DC voltage" in the R&V

table. In addition, we used the TLP250 module to drive MOSFETs. The TLP250 module will receive a 12V DC voltage.

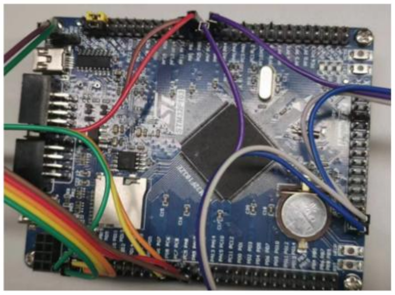
Voltage sensors: The type of current type voltage sensors is ZMPT101B. They will accept 220V AC power and transmit a sine wave to STM32F103 under a 5V DC power supply. It can provide appropriate compensation for AC terminals and accurately collect AC signals, including phases.

Transformers: The type of transformer is a 1:1.5 step-down transformer. It can withstand 30V AC voltage and has a rated power of 10VA.

STM32: The type of STM32 is STM32F103 which is an important part of the control system, and it will be specifically explained and described in the control system section.



Voltage Sensor: ZMPT101B



32-bit microcontroller IC: STM32F103

Figure 9: Voltage Sensor and Microcontroller

2.3 MTDC Subsystem

2.3.1 Overview

The MTDC subsystem stands for the multi-terminal DC Transmission System, which is essentially a connection hub connecting the RPC subsystem and external DC energy sources. We have two external DC sources in our design, a battery, and a solar panel.

However, they have different I-V characteristic curves for these two kinds of DC voltage sources. Batteries are stationary voltages source that will provide relatively constant output voltage unrelated to the output current. In contrast, the output voltage of a solar panel depends highly on the output current as shown in Figure 10. For this reason, we cannot simply connect these two power sources in parallel together. We need to convert these two output voltages into the same voltage level and then we can connect it to the RPC subsystem.

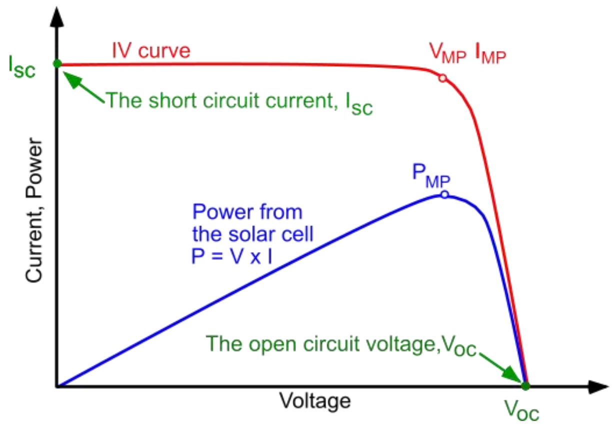


Figure 10: The I-V (red) and P-V (blue) characteristic of a typical solar panel

Consequently, the DC/DC converters that can convert the output voltage of different dc voltage sources to a unified voltage level are the core of the MTDC subsystem. For the battery, we need to design a DC/DC converter that can convert the 12V voltage from the battery to the (adjustable) 20V unified bus voltage. This DC/DC converter should be bidirectional and can allow current flow for charging and discharging the battery. For the PV panel, we need to design a DC/DC converter that can extract maximum power from the PV panel. In other words, we need to convert the VMP in Figure 10 into the (adjustable) 20V unified voltage.

2.3.2 Simulation

Since we manually select the bus voltage to be higher than the battery voltage and PV panel voltage, we design boost converters for these DC/DC converters. We build the circuits in MATLAB Simulink to prove the feasibility of the design and select appropriate component

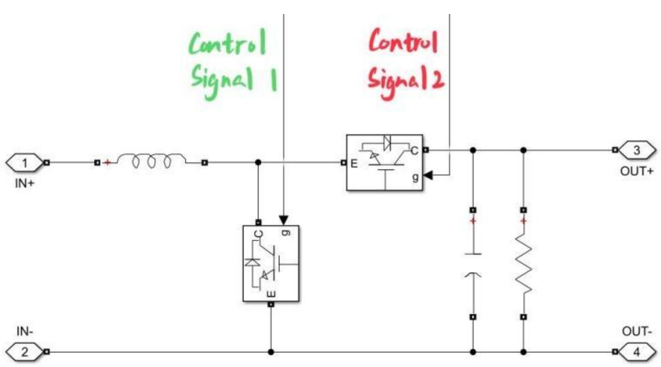


Figure 11: DC/DC boost converter circuit

values as shown in Figure 11.

IN represents the voltage at the energy storage side, and OUT represents the voltage at the DC bus side. MOSFETs in the circuit behave as switches and will be open or closed corresponding to the external control signal. The inductor at the input side makes sure there's input current throughout the cycle, while the output current through the upper right MOSFET depends on the duty ratio of the Control Signal 1. According to the formula:

$$V_{IN}I_{IN} = P_{IN} = P_{OUT} = V_{OUT}I_{OUT} \quad (1)$$

The OUT voltage at the bus depends on the duty ratio of Control Signal 1 and we can control the bus voltage by changing the duty ratio of Control Signal 1.

There's an RC (resistor and capacitor) filter at the bus side to reduce output voltage ripples. We have both Control Signal 1 and Control Signal 2 for the battery to ensure bidirectional DC/DC conversion. When we only feed Control Signal 2 to the DC/DC converter, the converter becomes a buck converter that can convert the high-voltage bus end to the low-voltage battery end, and we can use the extra energy from the traction network to charge the battery.

Based on the simulation results, when the output current is 0.1A we can make the output ripple at the bus side within ±1% of the open circuit DC bus voltage (20V) by using a switching frequency 5kHz and capacitor value of 200μF.

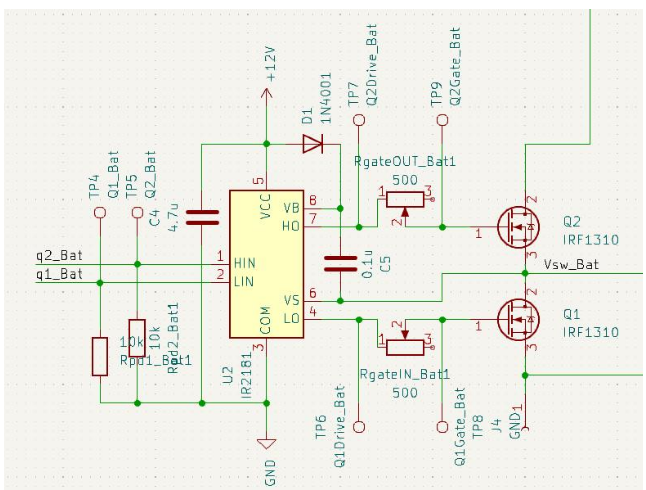


Figure 12: DC/DC Design Schematics

2.3.3 Actual Design

Figure 12 shows the actual schematics used for designing the power board of the MTDC subsystem. The part number for the MOSFETs is IRFI1310NPbF. Because real-life MOSFETs have internal capacitors and cannot be turned on or turned off immediately, we use extra MOSFET driver ICs IR2181 to provide the large current needed to charge or discharge these internal capacitors. The final power board is displayed in Figure 13. The capacitor value we used is 870μF.

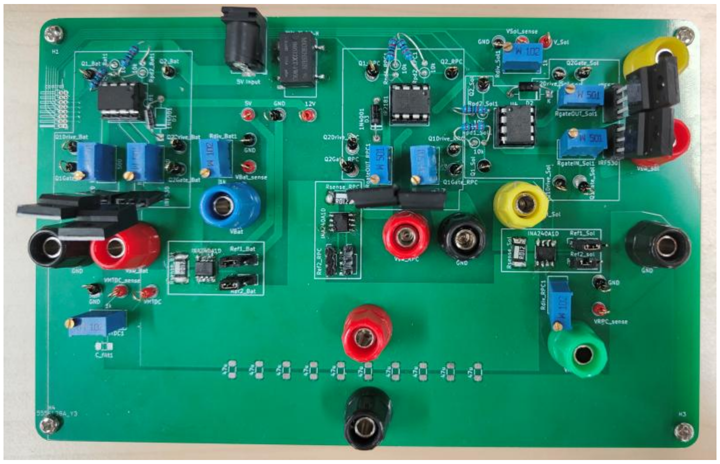


Figure 13: MTDC Subsystem power board

2.4 Control System

2.4.1 Overview

The control system in this project is divided into three main parts: controlling the sine pulse width modulation (SPWM) control signal of the AC/DC inverter, controlling the pulse width modulation (PWM) control signal of the DC/DC converter, and controlling the PWM control signal of the photovoltaic solar panel.

The first part is implemented on a microcontroller using a phase-locked loop (PLL) and PID control. The second part is implemented on an Arduino board using PI control. The third part is implemented on the Arduino board through the design of an MPPT algorithm (in this project, the perturb and observe method is chosen).

2.4.2 Simulation

The circuits for generating three control signals in Simulink are presented below. As shown in Figure 14, a computed sinusoidal waveform, with an initial phase and frequency (in this case, 50Hz), is compared to a sawtooth waveform. If the value of the sinusoidal waveform is greater than that of the sawtooth waveform, a value of 1 is output; otherwise, a value of 0 is output. This represents the SPWM control signal that satisfies the condition.

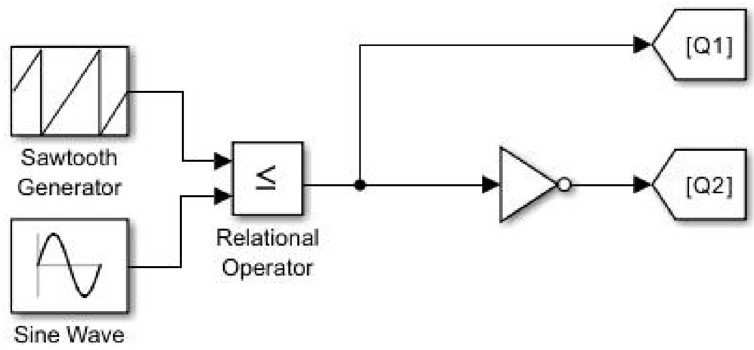


Figure 14: SPWM Generator Circuit

Figure 15 represents a PI controller. The constant on the far left is a pre-set arbitrary value that represents the desired output voltage of the circuit. The circuit takes the real-time sampled output voltage as an input and generates a PWM control signal with a corresponding duty cycle to regulate the output voltage.

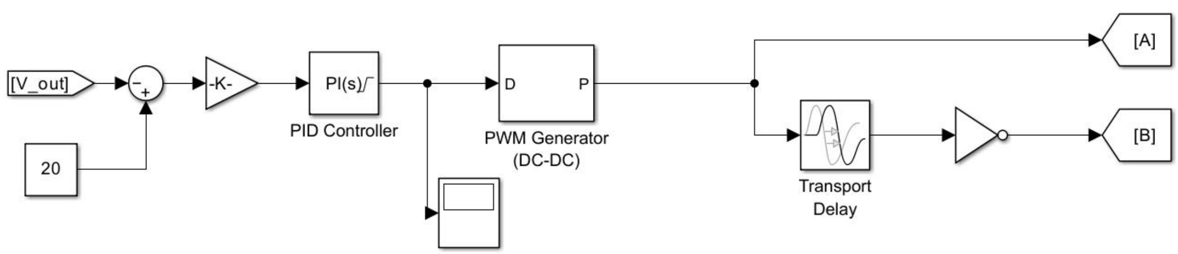


Figure 15: PI Control Generator Circuit

Figure 16 depicts the MPPT controller for controlling the photovoltaic solar panel. It takes the output voltage and current of the solar panel as inputs and calculates the current power. Using the perturb and observe method, it generates PWM control signals with different duty cycles to achieve maximum power point tracking.

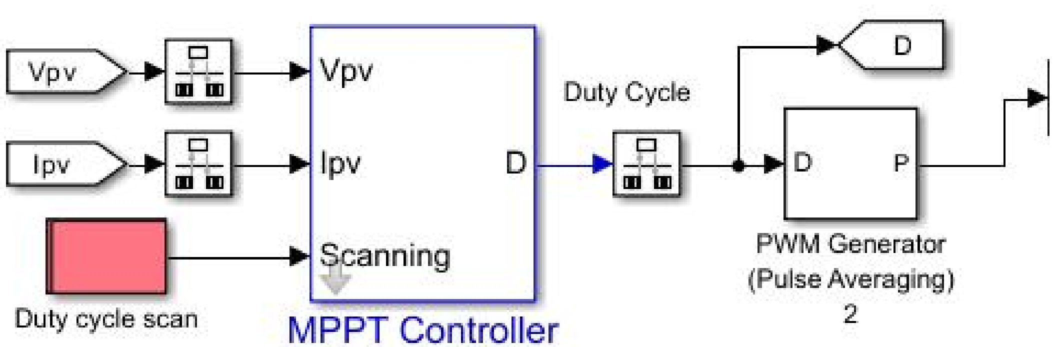


Figure 16: MPPT Controller Circuit

2.4.3 Actual Design

Due to the limited computational capabilities of Arduino, we employ a DSP to generate the SPWM control signal for controlling the AC/DC inverter.

Firstly, transform the input AC voltage from α/β frame to the dq frame in order to handle both amplitude and phase information.

```
//Park transformation
 //Alpha-beta frame -> dq frame.
   t_spll->VoltD = t_spll->CosWT * alpha + t_spll->SinWT *beta;
   t_spll->VoltQ = -t_spll->SinWT * alpha + t_spll->CosWT *beta;
```

Compare q-voltage and reference voltage, if there exists error between them, there is some difference between phase of the real voltage and phase of the reference voltage.

```
//PLL calculation
   pll->Ref = 0;
   pll->Fed = t_spll->VoltQ;
   pll->Err = pll->Fed + pll->Ref;//Calculate the error
```

Use the PID controller as well to track this error and calculate a new output for angular frequency.

```
//PID calculation
 pll->integral+=pll->Err;
  PLL_PID_out = pll->Kp * pll->Err;              /* Kp  */
   PLL_PID_out += pll->Ki * pll->integral;     /* Ki  */
 w_buf = 2 * M_PI*50+PLL_PID_out;  //50Hz
   //Angular frequency after filtering
 pll->LoopOut = 0.9f*w_buf+0.1f*pll->LoopOut;
```

Finally, Update the calculated phase using time integration and calculate the sin and cos values for next time park transformation.

```
 //Using t integration to update the calculated phase.
   t_spll->Theta += pll->LoopOut /20000.0f;
 //Calutate sin and cos for park transformation.
 t_spll->SinWT = arm_sin_f32(t_spll->Theta);
   t_spll->CosWT = arm_cos_f32(t_spll->Theta);
```

For PI control and MPPT control, we both implement using Arduino boards. For the PI controller, we initialize the pins for input and output and then set an arbitrary but reasonable value as a reference voltage. Parameters K_P and K_I are got by lots of training and adjustments.

```
const int analogPin = A0;  // Analog input
const int pwmPin1 = 8;  // Anolog output
const double referenceVoltage =20;  // Set any approprite value
const int fre=2500; //Frequency of the PWM control signal
double inputVoltage, outputPWM1=65;
double setpoint = referenceVoltage;
```

```
double Kp = 0.12, Ki = 6, Kd = 0.0;  // PID parameters
```

We set up the limitation of the PI controller to avoid too much oscillating and designed a voltage divider circuit to avoid the input voltage being larger than 5V, which would exceed the range of the board. Thus, this can finally output the PWM control signal in calculated duty and pre-set frequency (2,500 Hz).

```
int sensorValue = analogRead(analogPin);  // Read the input voltage
  inputVoltage = sensorValue * (5.0 / 1023.0) * 7.26 + 0.2100;
  // Transform input value to real voltage
  pid.Compute();  // Calculate the PI controller's output.
  int T=1000000/fre;
  double duty=outputPWM1*1.0/255;
  int dl=duty*T;
  for(int i=1;i<=100;i++){   //Output PWM signal of certain duty
    digitalWrite(pwmPin1,HIGH);
    delayMicroseconds(dl);
    digitalWrite(pwmPin1,LOW);
    delayMicroseconds(T-dl);
  }
```

For the MPPT controller, we used Perturb & Observe algorithm. If we find the power this time is larger than the preview one, it means we adjust the duty in the correct direction so just keep in this direction. Otherwise, we need to change the direction.

```
double power = inputVoltage * inputCurrent;
  // Compare the power this time and preview power.
  if (power > prevPower) {
    // If the power increases, move the duty in the same direction.
    if (prevAdjustment == 1) {
      outputPWM += stepSize;
    } else {
      outputPWM -= stepSize;
      prevAdjustment = -1;
    }
  } else {
 // If the power decreases, move the duty in the opposite direction.
    if (prevAdjustment == -1) {
      outputPWM -= stepSize;
    } else {
      outputPWM += stepSize;
      prevAdjustment = 1;
    }
  }
```

3. Design Verification

3.1 Traction System

We hope to output two voltages with a phase difference of 30 degrees and a value of 30V through a traction transformer, so we can test them through an oscilloscope.

The connection method of the transformer and the result of the oscilloscope are shown in Figure 17 and Figure 18, respectively.

Figure 17: connection of the traction transformer

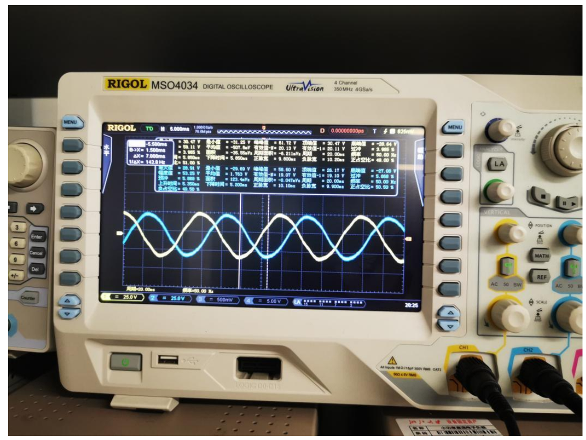


Figure 18: two outputs of the traction transformer

We can directly read the voltage value as 30V in the table. In addition, the measured time difference between the two outputs is 7ms, while the output frequency is 50Hz and the period is 20ms. Therefore, the corresponding phase difference is 126 degrees, which is within the error range.

3.2 Railway Power Conditioner (RPC)

For the RPC system, we hope it can balance the power under different phases of AC power. To test the ability of our RPC system to balance power, we will connect two AC terminals to the load ends of the traction system. We use two wattmeters to track the changes in voltage, current, and power of the load over time.

The two wattmeters are shown in Figure 19.

Figure 19: Hardware part of RPC

When we power up the system, the displayed values of the two wattmeters are different. As time goes on, the power difference between the two AC output terminals becomes smaller and smaller, ultimately achieving equality. This proves that RPC achieves power flow. Although the power at both ends is gradually decreasing, this is acceptable. Because there are electronic devices such as capacitors that absorb power. The data recorded in our experiment is shown below.

Table 1: Results and Analysis of the RPC

	Load A = 2483 Ω and Load B = 1494 Ω					
	A side			B side		
Time(s)	0	10	20	0	10	20
Urms(V)	229.42	229.42	229.42	228.61	228.6	228.62
Irms(A)	0.3426	0.3223	0.3126	0.3949	0.3536	0.3345
P(W)	78.419	73.608	71.425	88.614	79.743	75.602
S(VA)	78.60	73.95	71.72	90.27	80.83	76.47
Q(Var)	8.41	7.08	6.49	17.23	13.21	11.5
Analysis	88.614W - 78.149W = 10.465W					
	75.602W - 71.425W = 4.177W					

3.3 MTDC System

For the MTDC Subsystem, we want the unified voltage at the bus to be stable and look exactly like a DC voltage. That is, we want the ripple at the bus to be at little as possible. To test the ability of our MTDC Subsystem of stabilizing the bus voltage, we connect our power board to the battery and PV panel and check the output bus voltage.

As shown in Figure 20, the yellow line indicates the Control Signal1 that applies to the DC/DC converter, the purple line indicates the current flowing through the inductor in the DC/DC converter, and the blue line indicates the bus voltage. The bus voltage is nearly a straight line except for a bit of vibration during the switching of the control signal. This means that we successfully achieve the requirement of the MTDC Subsystem, and we successfully connect the battery and the solar panel.

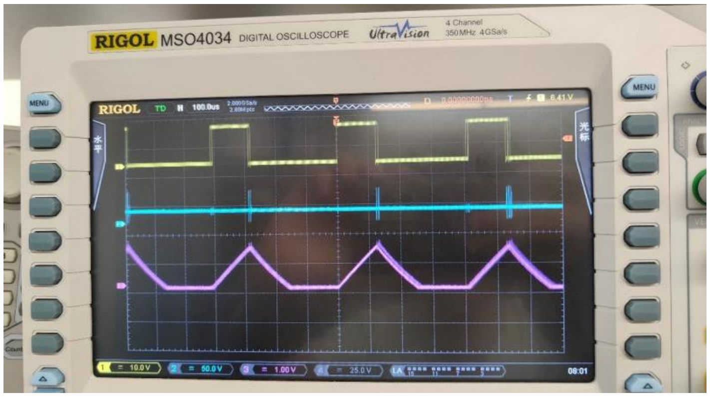


Figure 20: Result on the oscilloscope

3.4 Control System

For the control system, we conducted three experiments to validate the proper functionality of the PI controller in controlling the DC/DC converter. The experiments were as follows:

1. Rapid increase in load from 150Ω to 250Ω.

2. Rapid decrease in load from 250Ω to 150Ω.

3. Maintaining a constant load while abruptly increasing the reference voltage from 20V to 30V as specified in the code.

We observed and recorded the changes in the output voltage and presented the results in the following table:

Table 2: Output DC Bus voltage

Experiment	Load(Ω)	Reference Voltage(V)	t=0	t=2s	t=4s	t=6s	t=8s
#1	150->250	20	22.340V	21.962V	20.260V	20.102V	20.060V
#2	250->150	20	18.451V	19.481V	19.820V	19.961V	20.035V
#3	150	20->30	11.179V	28.458V	29.742V	30.002V	30.068V

It can be observed that the adjustment is completed within 6 to 8 seconds, meeting the sensitivity and adjustable range requirements as pre-designed.

4. Costs

4.1 Parts

Table 3: Parts Costs

Part	Manufacturer	Retail Cost ($)	Quantity	Total Cost ($)
Train (0-10kΩ potentiometer)	ALPS ELECTRO CO	0.80000	10	8.00
Step-down transformers (1.5:1)	Pulse Electronics	15.0	2	30.00
ZMPT101B	Zeminglangxi Inc	1.02	2	2.04
CRG40T65AN5H	CRMICRO	1.01000	8	8.08
L6388ED	STMicroelectronics	1.63000	8	13.04
STM32F103 Development Board	STMicroelectronics	30.96	1	30.96
EG8010	EGmicro	1.62	2	3.24
DC12-6800	REXUAV	37.99	1	37.99
Solar-power unit: 18V-10W panel	Kaiwen	24.5	1	24.50
PDS1-S5-D12-M	CUI Inc.	5.95000	2	11.90
IR2181PBF	Infineon Technologies	5.87000	2	11.74
IRFI1310NPbF	Infineon Technologies	2.27000	4	9.08
INA240A1D	Texas Instruments	3.96000	2	7.92
1N4001-T	Diodes Incorporated	0.20000	2	0.40
TLC/5A-102M-00	FASTRON GmbH	20.3500	2	40.70
E32D351HPN871TD79M	Shengda Microelectronics	2.72000	1	2.72
PCB Board	J@LC	1.7	10	17.00
Arduino® UNO R3	Arduino	27.60	1	27.60
1kΩResistor	Stackpole Electronics Inc	0.10000	11	1.10
10kΩResistor	Stackpole Electronics Inc	0.12000	12	1.44
47µF capacitor	Cal-Chip Electronics, Inc.	0.21000	11	2.31
0.1µF capacitor	Cal-Chip Electronics, Inc.	0.22000	11	2.42
4.7µF capacitor	Dontong Electronics	0.43000	2	0.86
Total	/	/	/	**295.04**

4.2 Labor

According to the UIUC's Computer Engineering average salary ($105325) and Electrical Engineering average salary ($79714), the fixed development costs are estimated to be 52$/hour for the ECE student, and 39$hour for EE students, 20 hours/ week for everyone.

$$\text{Total Labor Cost} = \text{hourly salary}(\$) \times (\text{hours/week}) \times \text{weeks} \times 2.5 \quad (2)$$

Table 4: Estimate of Labor Costs

Name	Hourly salary ($/hr)	Hours/week	Weeks	Total Cost ($)
Kai Zhang	39	20	14	27300
Jiebang Xia	39	20	14	27300
Jiakai Lin	52	20	14	36400
Yongcan Wang	39	20	14	27300
Total	/	/	/	**118300**

4.3 Grand Total

Since we are just doing a modeling of the actual power conditioner, the voltage we used is step-down voltage which is only $\frac{1}{1000}$ of the actual voltage level. If this product is used in real life, the parts cost will be approximately $200\times$ times higher to tolerate high voltage and high power. So the grand cost is about $295.04\$ \times 200 + 118300\$ = 177308\$$.

5. Conclusion

5.1 Accomplishments

In this report, we demonstrate a Railway Power Conditioner that can balance the inequivalent power of two ac sources. For one thing, the RPC Subsystem successfully transfers the AC voltage of the traction network with excess power to a DC voltage. Then it inverts the DC voltage back to an AC voltage to compensate for the power shortage at the other end of the traction network. This AC-DC-AC conversion enables a current flow between two traction networks, which meet our requirements of balancing inequivalent power on the power grid and improving power quality.

For another, the MTDC subsystem provides ports for green energy and creates a microgrid. We have succeeded in making use of batteries as a reservoir to store electricity and making use of solar panels to achieve the sustainability objective of our projects.

In all, our project managed to satisfy our goal of balancing inequivalent power for different power lines, and meanwhile, we apply renewable energy to our project to meet the requirements of the green energy era.

5.2 Uncertainties

Despite we have proven the functionality of our design, there are some uncertainties and need further modification.

Firstly, one key uncertainty is that when we debug the RPC system, the power at both AC ends of the RPC is decreasing. As previously recorded in the design verification, the power of the A side decreased from 78W to 71W within 20 seconds, while the power of the B side decreased from 88W to 75W within the same time frame. We speculate that there may be a loss of power, or there may be electronic components absorbing energy, such as capacitors. There may be another possibility that the temperature of the load will gradually increase, which results in an increase in resistance over time. According to $P = \frac{U^2}{R}$, the dissipated power will decrease. But this power reduction is small, which shouldn't contribute fully to the 7W or 13W drop.

Besides, what we have built is just a model proving the feasibility of our design. The external grids we used are the 220V power line, but the external grids for the railways are high-voltage power lines rated up to 220kV. Our toy model will break under such high-voltage and high-power conditions. Even though we may replace the electronic devices with those that can tolerate higher voltage and power, we are not sure whether the same design will function properly without testing thoroughly under high-voltage conditions.

5.3 Future Work / Alternatives

1. Improve the ability to balance power. It includes reducing the time for power to reach balance and balancing power with larger differences.

2. Use wind energy. This increases the difficulty of the project and the types of renewable energy utilization. We need the wind turbine that generates variable AC power, and an AC/DC converter to connect the wind turbine to the MTDC.

3. Optimize the control method. For example, use a double closed-loop control method and different transformer structures (Scott traction transformer).

4. Building a more robust RPC system and testing under real-life 220kV power girds.

5.4 Ethical Considerations

5.4.1 Safety

In the project of a High-renewable microgrid for Railway Power Conditioner (RPC), we must first ensure the personal safety and property integrity of citizens. The RPC circuit must be reasonable and safe. We will strictly test and check the circuit to prevent accidents. We must follow the ACM Code of Ethics and Professional Conduct 1.2 Avoid harm [6].

5.4.2 Environmental protection

Highly renewable is our second purpose. We must ensure that all parts of the project must not cause unreasonable damage to the environment, especially the battery and three-phase voltage source. In order to ensure the public welfare of the world, we adhere to the ethical design and sustainable development practices, which follow the IEEE Ethics guidelines 1.1 [7].

5.4.3 Privacy

Our control subsystem must ensure that the train operates in a safe and stable manner, which inevitably contains train data (public privacy). The data of the train must be properly and safely stored. Without explicit consent, others are not allowed to access and share personally. We must follow the ACM Code of Ethics and Professional Conduct 1.6 Respect privacy [6].

References

[1] F. Ma, Q. Xu, Z. He, et al., "A railway traction power conditioner using modular multilevel converter and its control strategy for high-speed railway system," IEEE Transactions on Transportation Electrification, vol. 2, no. 1, pp. 96–109, 2016.

[2] Z. Shu, S. Xie, K. Lu, et al., "Digital detection, control, and distribution system for co-phase traction power supply application," Industrial Electronics, IEEE Transactions on, vol. 60, no. 5, p.1831–1839, 2013.

[3] W. Wei, L. Wu, J. Wang, and S. Mei, "Expansion planning of urban electrified transportation networks: A mixed-integer convex programming approach," IEEE Transactions on Transportation Electrification, vol. PP, no. 1, pp. 1–1, 2017.

[4] M. E. Choi, S. W. Kim, and S. W. Seo, "Energy management optimization in a battery/supercapacitor hybrid energy storage system," IEEE Transactions on Smart Grid, vol. 3, no. 1, pp. 463–472, 2012.

[5] S. F. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," Renewable sustainable energy reviews, no. Apr. P. 20, 2013.

[6] ACM. ""ACM Code of Ethics and Professional Conduct"." (2018), [Online]. Available: https://www.acm.org/code-of-ethics (visited on 03/08/2023).

[7] IEEE. ""IEEE Code of Ethics"." (2016), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 03/08/2023)

Appendix

A Requirement and Verification Table

Table 5: Requirements and Verification of the Traction Subsystem

Requirement	Verification	Verification status (Y or N)
The transformer successfully transforms the external three-phase power grid into two one-phase power supplies with a 120° phase difference.	Connect the input end of the traction transformer to the socket in the laboratory, and use an oscilloscope to record the inputs and outputs of the transformer. The output voltage waveform should meet the following requirements: 1. The RMS value of both output waveforms should be around 22V. 2. Both outputs have the same sinusoid shape as the input. 3. The phase difference between the two output phases is 120°.	Y
The filter in the subsystem successfully filters out irrelevant harmonics and only keeps sinusoidal waves around 50Hz.	Use an oscilloscope to measure the voltage at the traction network. The voltage waveform should meet the following requirements: 1. The waveform looks exactly like a sinusoid wave with little distortion. 2. Perform a Fast Fourier Transfer on the voltage data. The highest peak should be around 50Hz, and its magnitude is much larger than other frequencies.	Y

Table 6: Requirements and Verification of the RPC Subsystem

Requirement	Verification	Verification status (Y or N)
The RPC system can transfer an AC voltage to a DC voltage and outputs a stable 20V DC voltage with ripple within ±5% of the open circuit DC RPC output voltage.	Connect the input voltage of the RPC subsystem to a 22V RMS AC voltage signal. Use an oscillator to check the output DC voltage of the RPC subsystem. The DC voltage should meet the following requirements: 1. The average voltage is 20V. 2. Measure the maximum DC output and minimum DC output. The difference ΔV should be within 1V.	Y
The RPC system can transfer a DC voltage to an AC voltage and outputs a sinusoidal-like 22V RMS AC voltage.	Use DC ports of the RPC subsystem as the input and connect it to a 20V voltage DC source. Measure the voltage at the AC ports of the RPC subsystem: 1. The waveform looks almost like a sinusoid wave with some distortion. 2. The RMS voltage of the AC ports is around 22V (within ±10% tolerance).	Y

Table 7: Requirements and Verification of the MTDC Subsystem

Requirement	Verification	Verification status (Y or N)
The MTDC system can transfer the battery and PV panel voltage to a unified, stable 20V DC voltage with ripple within ±1% of the open circuit DC RPC output voltage.	Connect the battery and the solar panel to the MTDC subsystem. Use an oscillator to check the bus voltage of the MTDC subsystem. The bus voltage should meet the following requirements: 1. The average voltage is 20V. 2. Measure the maximum DC output and minimum DC output. The difference ΔV should be within 0.2V.	Y

Table 8: Requirements and Verification of the Control Subsystem

Requirement	Verification	Verification status (Y or N)
The proper control signal is applied on the RPC Subsystem and power can successfully be converted from one AC side to the other AC side.	Use a 1.5kΩ resistor to simulate one train and a 2.5kΩ resistor for the other. Connect them to two AC ports of the RPC subsystem respectively. Apply 22V RMS voltage on each side of the port and use wattmeters to get the power on each traction network. The reading on two wattmeters should become close within the 60s.	Y
The proper control signal is applied on the MTDC Subsystem, and the bus voltage is constant regardless of the traction force of the trains (the resistances that simulate the trains).	Connect the battery and the solar panel to the MTDC subsystem. Connect a resistor to the bus to simulate the load of trains. Use an oscillator to check the bus voltage of the MTDC subsystem. The bus voltage should meet the following requirements: 1. Suddenly increase the resistor from 150Ω to 250Ω, the bus voltage returns to 20V within 15s. 2. Suddenly decrease the resistor from 250Ω to 150Ω, and the bus voltage returns to 20V within 15s.	Y
The proper control signal is applied on the MTDC Subsystem, and the bus voltage can be any reasonable user-specified voltage higher than 12V.	Connect the battery and the solar panel to the MTDC subsystem. Set the reference bus voltage to 20V. Use an oscillator to check the bus voltage of the MTDC subsystem. Then change the reference bus voltage to 30V. The bus voltage should meet the following requirements: 1. The average bus voltage is 30V (0.1V difference at most). 2. Bus voltage increases from 20V to 30V within the 60s.	Y
The Proper control signal is applied on the MTDC Subsystem such that maximum power is extracted from the solar panel	Use Arduino to scan different output voltages and get an I-V characteristic and thus a P-V plot of the solar panel. Use an oscillator to check the solar panel end of the DC/DC converter. The voltage at the end should be the voltage that maximizes power in the P-V plot. The difference between the measured voltage and the maximized voltage should be within 0.5V.	Y