ECE 445

SENIOR DESIGN LABORATORY

PROPOSAL

High-renewable microgrid for Railway Power Conditioner(RPC)

Team #30

JIEBANG XIA (jiebang2@illinois.edu)
YONGCAN WANG
(yongcan2@illinois.edu)
KAI ZHANG (kaiz5@illinois.edu)
JIAKAI LIN (jiakail2@illinois.edu)

Sponsor: Lin Qiu

April 3, 2023

Abstract

In real life, the external power supply system of electrified network is a three-phase power supply, while the electrified railway traction network usually involves only two phases. Therefore, at the junction of lines with different two phases, the power line power consumption and phase will not match. In this regard, we designed a railway power conversion hub (RPC) to achieve power balance when the selected three-phase input on the break point of the traction network changes, and provide a method to improve energy efficiency by using regenerative braking energy. Finally, it can improve the power supply quality and the stability of traction network.

Contents

1 Introduction

1.1 Problem

Electrified railways have the characteristics of high safety factors, high comfort, large transportation capacity, and low time consumption, which are effective means to solve traffic inconvenience. However, with the rapid development of electrified railways, power quality issues such as harmonics and negative sequence have also received widespread attention. At the same time, more and more issues in the traction power supply system where regenerative braking energy cannot be effectively utilized have also emerged. Currently, in traction substations, fees are charged based on the two-part electricity price, and the problem of ineffective utilization of regenerative braking energy can lead to higher fees charged by the two-part electricity price and significant economic impact. To be more specific, In real life, the external power supply system is in three-phase while the traction network of an electrified railway usually only involves two phases. If we randomly select two phases out of the three-phase power grid, there will be a mismatch in the power consumption for each power line. We need to come up with an idea to balance the power consumption on each power line. Besides, during the operation of electrified railways, the environment is not stable and small disturbances may exist on the system, which requires our system to have resilience in eliminating those disturbances. For example, the friction between the train and the ground varies in different areas and the train may climb up a ramp sometimes. In order to make the train operate at a uniform velocity, we cannot simply exert unified traction. It's also impossible for the power supply voltage to remain the same and there must be some small vibration. It's vital to make the train function properly unchanged when the outside environment changes.[1]

1.2 Solution

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, then 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 Visual Aid

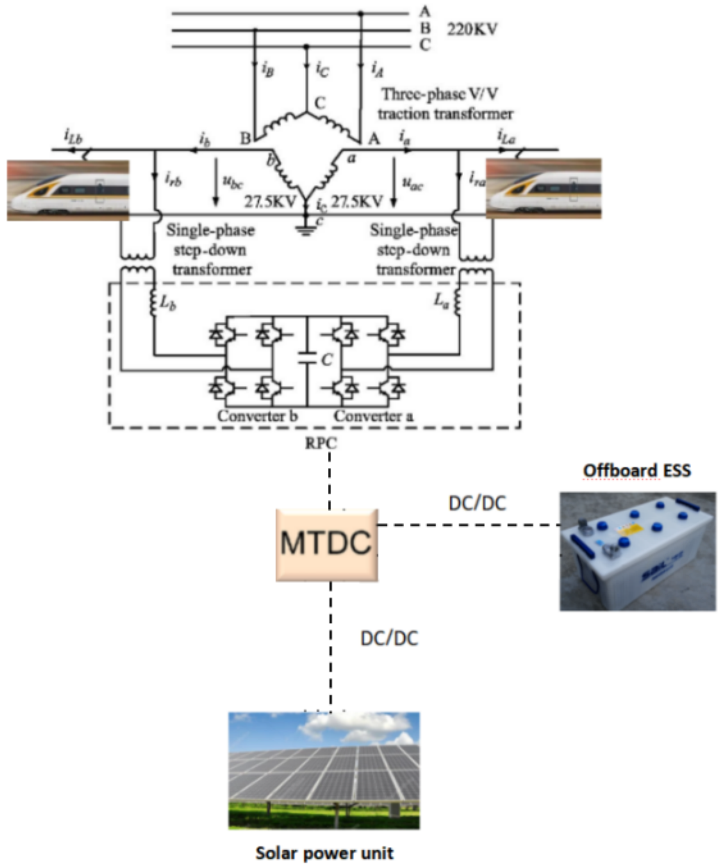

Figure 1: Visual Aid of RPC

1.4 High-Level Requirements List

We will have a list of three quantitative characteristics to solve the problem. These requirements are considerably important, which respectively prove that the whole system has great abilities for power-balance, anti-interference, and being stable.

1. The whole system has a great ability for anti-interference. We will exert some interference on the system to evaluate its stability. When we simulate that the train needs to increase traction during going uphill or upwind, we will connect potentiometers (0-10k $Omega$) in series on the train load. The DC voltage at RPC will reach stability in 10 seconds to prove that the system has relatively good elasticity. At the same time, the voltage at both ends of the battery must not change.

2. RPC has perfect function to dynamically balance the interphase active power. Two AC voltage sources with different phases are converted into the same DC voltage through RPC, which means the two voltages on either side of the breakpoint are connected. At the same time, the power difference between the two phases cannot be too small. It must be

proved that RPC has the coordination ability to balance the power difference of at least 100W.

3. The voltage stability of each port of MTDC also needs to be guaranteed. In the final simulation, it can pass the test. RPC and battery ports should always be stable, even if there is disturbance (less than 1V), they must be very small. However, the port of the solar panel should change with time and load, in order to meet the maximum power extraction and make full use of renewable energy.

2 Design

2.1 Block Diagram

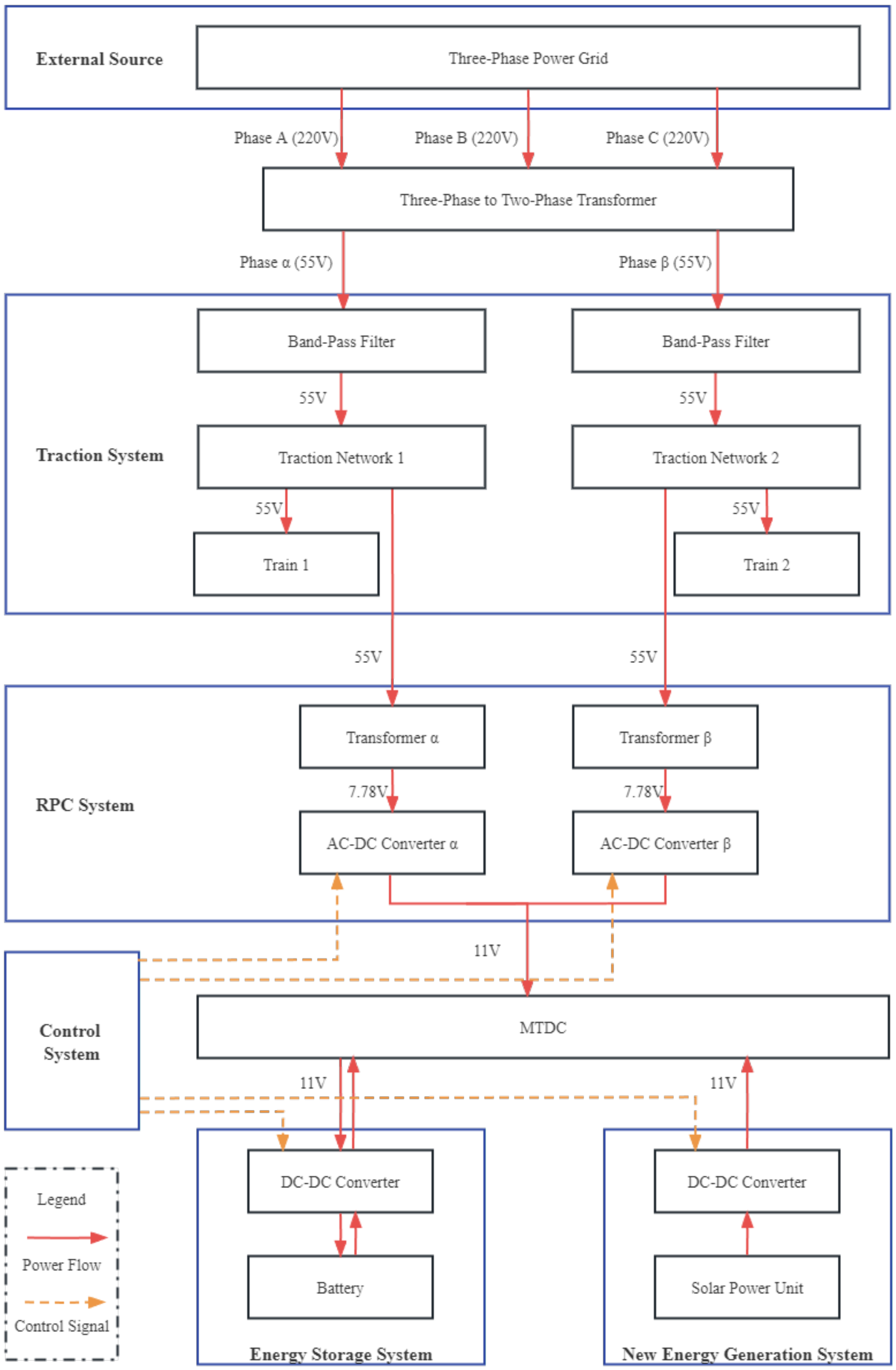

Figure 2: Block diagram for the RPC System.

2.2 Subsystem Overview

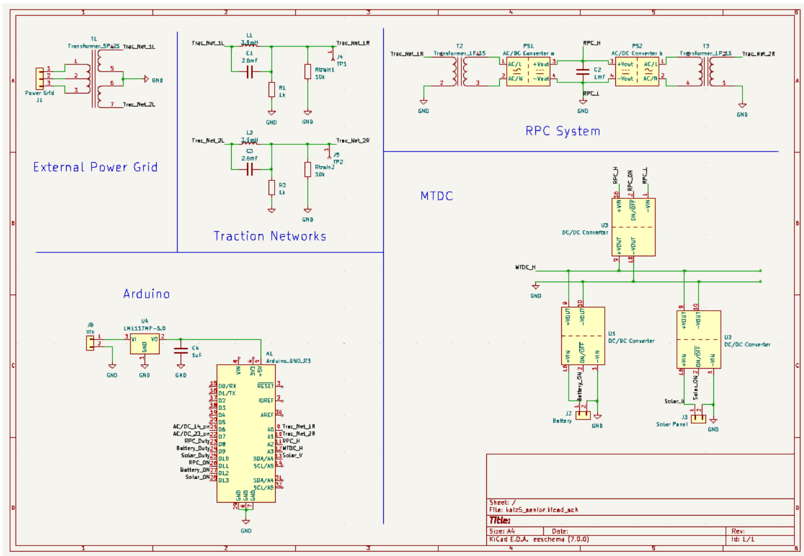

Figure 3: Overall schematic diagram of the subsystems.

2.2.1 Railway Power Conditioner (RPC)

The RPC subsystem is the main subsystem of this project. The RPC system is connected to the traction system and MTDC. To be more specific, AC-DC converters are directly connected to transformers under two trains, and the whole system aims to dynamically balance the inter-phase active power, independently compensate the reactive power of each feeder and suppress its harmonics. We will use transformers and AC/DC converters in this subsystem. Transformers are used to step down the 55V high voltage at the traction network to a relatively safe low voltage (7.78V) to handle. AC/DC converters are used to eliminate the phase difference at the two sides of the breakpoint and make it possible to connect them.[3].

2.2.2 Control system

The control system is the algorithm part of the project. We will use control theorems to make the train run in a safe and stable manner. It will connect and affect RPC and MTDC. We will start with open-loop control, and we will design PID closed-loop control later. We will also try data-driven maximum power point tracking control to extract maximum power from the solar panel in ten seconds. Through designing control signals for switching functions from Arduino, some switches can be opened or closed to achieve the purpose of those converters.

2.2.3 MTDC (Multi-terminal dc transmission control system)

The MTDC is the bus that connects RPC and other sources from the microgrid (like photovoltaic, battery, and even wind power). We need to design an MTDC that can satisfy our different expectations. For RPC and battery, we need a stable voltage reference, while for solar panels, we need to change the DC voltage value to extract maximum power. This can be realized by designing a proper DC/DC converter for each component.

2.2.4 Traction system

The traction system is a system that provides traction for trains, including trains, loads, power grids, and band-pass filters. The three-phase voltage source is the external voltage source that supplies power to the system. Band-pass (RC) filters are used to suppress harmonics from the output of the three-phase to two-phase transformer and provide a 50hz, 55VAC voltage to the traction network. We will use a safer 220V three-phase power socket instead of using a 110kV/220kV external power grid. We will build a microgrid to drive the train and use power detection to realize simulation.[4].

2.3 Subsystem Requirements

2.3.1 Traction system

First of all, there is a 220V three-phase power grid in this system. Secondly, we believe that the most important part of the system is the traction transformer, whose main function is to transform the three-phase high-voltage power provided by the power grid into single-phase power used by the traction network. In our project, we will convert 220V three-phase electricity into 55V single-phase electricity. For this transformer, we will connect two single-phase transformers in V-shape. 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 is connected to the traction network, and the other end is connected to the return ground line in the form of a common endpoint. [5].

2.3.2 Railway Power Conditioner (RPC)

There are two transformers and, two AC-DC converters, and two high-pass filters for each breakpoint in the traction network. These transformers are step-down transformers, which reduce the voltage in the power supply arms of the traction network from 55V to 7.7V and connect it with the AC/DC converter. The outputs of these two AC/DC converters, which is the output port of the RPC, are connected to the MTDC. A capacitor is also connected to the output port and provides stable DC voltage to the two converters. The two converters of RPC can be controlled as a controlled current source, which can realize a two-way flow of active power between two phases and carry out harmonic suppression and reactive compensation. In essence, the converter in RPC is a bidirectional PWM rectifier structure. The high pass filters are connected directly to the traction network to filter out high-frequency irrelevant harmonics.

This is one of the AC/DC converters in RPC. It is the circuit represented by a block in the upper right of the schematic diagram in the Subsystem Overview. It consists of basic capacitors, resistors, inductors, and multiple SCRs. The data for each component is shown in the figure, and these are the results of our repeated simulations.

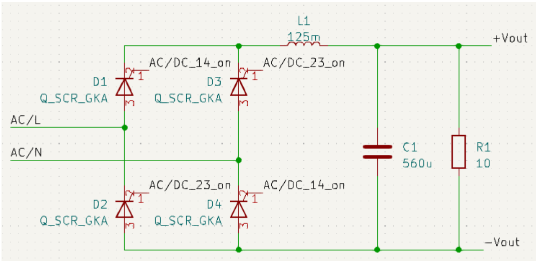

Figure 4: AC/DC converter.

2.3.3 MTDC

As a bus connecting RPC and coordinating the energy system, MTDC is an indispensable connection hub. It can meet our different expectations, for example, to make the most efficient use of sustainable energy such as solar energy.

The energy system acts as a large reservoir. During this period, it will absorb additional power or provide backup power, and use renewable energy. As shown in the figure, the energy system is divided into an energy storage system and a new energy generation system. The energy storage system is also irreplaceable. Once it is lost, the system will not be able to compensate for the power to the traction system, and the unused additional power of the grid will also be lost, which is not in line with the principle of sustainable development.

The energy storage system is mainly composed of DC/DC converter and battery. The battery can provide additional energy for the traction system at necessary time or store excess energy. The bidirectional DC/DC converter connected to it is designed to maintain a stable voltage of 11V (adjustable) at both ends of the battery and compensate for at least 100W of power. We can charge or discharge the energy storage medium by controlling the bidirectional DC/DC converter. When the bidirectional DC/DC converter is in buck mode, the storage device is charged. When the bidirectional DC/DC converter is in boost mode, the storage device is discharged.

The new energy generation system is the environmentally friendly goal of our project. It will maximize the use of solar energy and even wind energy to compensate for the power of the entire railway system. The DC/DC converter of the solar panel should not ensure that the voltage at both ends of the solar panel is always 11V (adjustable) but should ensure that the current (power) is changeable to extract maximum power instead. If we use additional wind energy to generate electricity, we must use AC/DC converter to ensure that the constant DC voltage output to the bus is 11V (adjustable). Since the capacity of new energy varies with the environment, we do not request it to provide a constant amount of power.

DC/DC converters that connect various other components are the core part of MTDC. The following is a schematic diagram of DC/DC converters, which is an invisible part of the Subsystem Overview. Obviously, when a DC/DC converter is connected to a battery, it can change to a buck mode or boost mode depending on the situation.

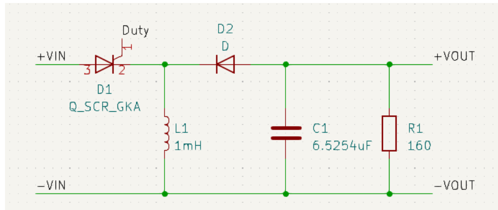

Figure 5: DC/DC converter.

2.4 Tolerance Analysis

1. The voltage of our whole system is reduced from 220V domestic electricity, so there is a huge gap between it and the actual 220kV railway power grid. This may mean that when the voltage level of the three-phase power grid changes, some of the electric component will fail (require greater compensation and anti-interference functions), and the whole system will not meet the requirements of power balance. Although this is a huge challenge of the project, we can still adjust it by replacing those capacitors, inductors, resistors, or transistors with power electronics devices that can tolerate large voltage or current. These devices may have new electronic characteristics, but we can redesign the voltage level of each wire to meet these requirements.

2. Since it takes time for the semiconductors to act in response to the changing input, the whole system has an inevitable delay between each part. For example, there are AC/DC converters in the RPC (Railway Power Conditioner), and there also are converters between the RPC port and recyclable energy connected by MTDC. The accumulation of these delays will inevitably increase the delay time and create greater uncertainty. However, we have an extra control system that is in charge of the behavior of those converters. We can record the delay in the past and use proper control methods to eliminate the effects of delay in advance.

3. The connection mode of our project is based on the traditional v-v transformer. Although it has simple wiring and high-capacity utilization, it is also easy to form a single-phase power supply and negative sequence serious power supply environment. To ensure the stability of RPC intermediate DC voltage, we can optimize the control strategy. For example, we can use a double closed-loop control strategy and different transformer structures (Scott traction transformer). In addition, it has unique advantages in power quality control of traction power supply systems.

4. The 220V domestic electricity is not stable and there may be some small variation signals, and the train may not move smoothly and need larger or smaller traction from time to time. As a result, the voltage of the traction network may not be stable and thus the voltage of the RPC port on MTDC may vary. We can solve this problem by connecting a high pass filter to each traction network and filtering out variations at higher frequencies. Mainly the original 50Hz AC signal is left on the traction network and the whole system will be more stable.

Through our simulation on MATLAB, we design a filter that obtains 50HZ and filters out other frequencies. We use RCL loops for analysis. We select the appropriate specifications for resistors, capacitors, and inductors. The values of each component and the principle formula of the filter are shown below. At the same time, we simulate the filtration curve of the filter for different frequencies.

$$R = 1000\Omega$$

$$C = 3.9 \times 10^{-3} F$$

$$L = 2.6 \times 10^{-3} H$$

$$\left.\frac{V_{\text{out}}}{V_{\text{in}}}\right|_{pLC} = \frac{j\omega L}{R_S\left(1-\omega^2 LC\right)+j\omega L}$$

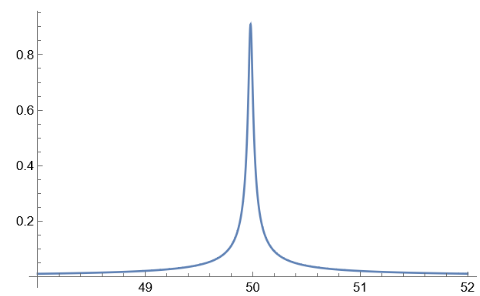

Figure 6: The filtration curve.

3 Ethics

3.1 Safety

In the project of 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].

3.2 Environmental protection

High-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 ethical design and sustainable development practices, which follow the IEEE Ethics guidelines 1.1[7].

3.3 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].

4 Safety

Safety is the most important for us. We must complete the project on the premise of ensuring safety.

First of all, we will strictly abide by the basic safety principles. For example, at least two people are present when we do experiments in the laboratory. Each of our team members will complete the safety training in the laboratory and get high marks on the test.

Secondly, we have different safety requirements for each component, and we will study the safety of components. For example, the transformer will produce a large voltage, so we will focus on checking its safety. Before use, we will check its fuse, check its insulating sleeve, and detect its load during use. If during the experiment, a transformer experiences some faults that generate a large current, the fuse can be immediately disconnected to ensure the safety of the experimenter's life. When using the converters, we will check whether the incoming line voltage of the power supply is normal before starting the machine, and we will check that all indicators and marker lights are in good condition. According to our design, the input and output voltage of the converters are far less than the safe voltage (36V) that the human body can withstand, so even if all safety measures fail, the experimenter will not be in danger. Besides, when we select components, we will select the components that are most suitable for our operation and have the highest safety factor.

In addition, because many circuit components are used, we will check the short circuit problem of the circuit, and wear insulating gloves and other insulating equipment to avoid direct contact with electricity. We also cut off the power supply when detecting or replacing components to avoid live operation.

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).