Warsaw University of Technology

FACULTY OF ELECTRICAL ENGINEERING

Electrical Power Engineering Institute,
Division of Traction and Electrical Power Economics

Bachelor’s diploma thesis

in the field of study of Electrical Engineering
and specialisation in Electrical Engineering

Development of a Virtual Simulator for Analysis of Voltage Drops and Short Circuits in the DC Traction Power Supply System

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Abstract

Development of a Virtual Simulator for Analysis of Voltage Drops and Short Circuits in the DC Traction Power Supply System

The introduction of electric traction systems has led to the development of railway operations with efficient ways of powering electric locomotives. To maximize this efficiency, various research studies have been conducted regarding the operational reliability, safety, and impact of electrified railway systems within urban environments. Laboratory experiments, mathematical modelling, and real-world performance data analysis often support these investigations. As the importance of this area is clear and needed, a dedicated laboratory course within the Electrical Engineering curriculum at Warsaw University of Technology focuses explicitly on research regarding electrified railway traction systems. The bachelor’s thesis is dedicated to the modernization of the laboratory exercise of the Electric Traction course by extending or replacing the physical workbench with a new virtual simulator. Although the existing laboratory workbench is still functional, it is significantly limited by the parameters of its physical components. The virtual simulator is developed in this thesis to avoid these limitations and deliver improved accuracy, precision and a more comprehensive range of possible parameters of the modelled system. The simulator created in this thesis can model the basic electrical parameters of the 3 kV DC traction system, with the possibility of selecting substation and traction network parameters for a few modes of operation – the passage of a single train and a short circuit in the traction system. Python is the language chosen for the development of the simulator. Its rich libraries will deeply contribute to the development of a user-friendly interface. The development of this virtual simulator allows students to conduct more comprehensive analyses using a broad range of parameters. It extends the range of tests in the laboratory classes performed on the physical workbench. In addition, it is expected to enhance the accuracy of the results and reduce the potential human error, thereby improving the overall quality of conducted research.

Keywords: virtual simulator, Python, electric traction, railway, substation voltage, pantograph voltage, traction current, voltage drop, catenary, short circuit.

Streszczenie

Opracowanie wirtualnego symulatora do analizy spadków napięcia i zwarć w systemie zasilania trakcji prądu stałego

Wprowadzenie elektrycznych systemów trakcyjnych doprowadziło do rozwoju operacji kolejowych z wydajnymi sposobami zasilania lokomotyw elektrycznych. Aby zmaksymalizować tę wydajność, przeprowadzono różne badania dotyczące niezawodności operacyjnej, bezpieczeństwa i wpływu zelektryfikowanych systemów kolejowych w środowiskach miejskich. Badania te są często wspierane eksperymentami laboratoryjnymi, modelowaniem matematycznym i analizą danych dotyczących wydajności w warunkach rzeczywistym. Ponieważ znaczenie tego obszaru jest oczywiste i potrzebne, dedykowany kurs laboratoryjny w ramach programu nauczania elektrotechniki na Politechnice Warszawskiej koncentruje się konkretnie na badaniach dotyczących zelektryfikowanych systemów trakcyjnych kolei. Praca inżynierska jest poświęcona modernizacji ćwiczenia laboratoryjnego stosowanego w kursie Trakcja Elektryczna poprzez uzupełnienie lub zastąpienie fizycznego stanowiska nowym wirtualnym symulatorem. Chociaż istniejące laboratorium nadal działa, jest ono znacząco ograniczone poprzez stosowane w nim fizyczne elementy układu. Wirtualny symulator jest rozwijany w tej pracy, aby uniknąć tych ograniczeń i zapewnić lepszą dokładność, precyzję i większy zakres możliwych parametrów modelowanego systemu. Stworzony w niniejszej pracy symulator zdolny do analizowania podstawowych parametrów elektrycznych systemu trakcji 3 kV DC, z możliwością wybory parametrów podstacji, sieci trakcyjnej dla kilku trybów pracy – przejazd pojedynczego pociągu i zwarcia w systemie trakcyjnym. Python jest językiem wybranym do opracowania symulatora. Jego bogate biblioteki w znacznym stopniu przyczynią się do opracowania przyjaznego dla użytkownika interfejsu. Opracowanie tego wirtualnego symulatora pozwala studentom na przeprowadzanie bardziej kompleksowych analiz, przy użyciu szerokiego zakresu parametrów, a także rozszerza zakres testów w zajęciach laboratoryjnych wykonywanych na fizycznym stanowisku. Ponadto oczekuje się, że zwiększy on dokładność wyników i zmniejszy potencjalny błąd ludzki, poprawiając tym samym ogólną jakość prowadzonych badań.

Słowa kluczowe: wirtualny symulator, Python, trakcja elektryczna, koleje, napięcie podstacji, napięcie na pantografie, prąd trakcyjny, spadek napięcia, sieć trakcyjna, zwarcie.

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Table of content

1. Introduction

The railway operations have significantly improved by the introduction of electric traction systems by offering efficient means of powering electric trains. There has been extensive research conducted to improve the operational reliability, safety and implications of electrified railway systems in urban environments in order to maximize the efficiency [1].

The thesis aims to develop a virtual simulator for the simulation of voltage drop on the pantograph of railway vehicles and short circuits in the 3 kV DC traction system used in the Electric Traction course at Warsaw University of Technology. While the existing conventional laboratory stand is functional, modernization is necessary as some parts do not function as expected.

The main scope of this thesis includes the design and implementation of a virtual simulator for the simulation of voltage drop on the pantograph of a single railway vehicle and short circuits in the 3 kV DC traction system. The simulator allows configuring basic parameters:

- type of railways;
- type of simulation;
- type of traction power system (one-sided, two-sided, two-sided with sectioning cabin);
- parameters of traction substation, catenary system, rail system.

The simulator is developed using Python, one of the famous programming languages. Python has been chosen because of its extensive library that can create a powerful and intuitive graphical user interface. This thesis focuses only on the software aspect to increase the accuracy and precision of the analysis conducted without including the physical configuration of the hardware.

The engineering goal of the thesis is to demonstrate the author's competence in software development by creating a tool that provides students with the ability to perform comprehensive analyses with a broader range of parameters. This achievement is intended to improve the accuracy of results, minimize potential human error, and thereby elevate the overall quality of the research conducted within the Electrical Engineering program.

The scope of the thesis does not include:

- simulation involving multiple trains simultaneously;
- simulation of metro, tram, and light rail systems (these are reserved for potential future development);
- simulation of AC railway systems (this is also a potential area for future development);
- automated train operation functionality.

2. Theoretical background regarding DC traction power supply

A DC traction substation is a critical component of the rail transportation infrastructure in order to ensure a reliable and consistent power supply to the tracks and trains. The primary purpose of a DC traction substation is to draw high-voltage or middle-voltage AC power from the utility power supply and convert it into the DC power needed to operate electric trains. A DC traction substation typically consists of several key parts, including transformers, rectifiers, and switchgears [2].

In order to meet the specific needs of the railway system, the considerations such as the location of the substation relative to the rail network, the capacity required to meet peak demand, and the integration with the overall DC power supply system are involved in the construction of a DC traction substation in addition to the primary components [3]. With all the primary components in the substation, the DC power supply system also includes the overhead lines that deliver power to the trains, together with the return circuits that ensure the completion of the electrical circuit. Understanding the operation and the construction of DC traction substations and the role of each component is crucial for ensuring safe and efficient operation of electric railways.

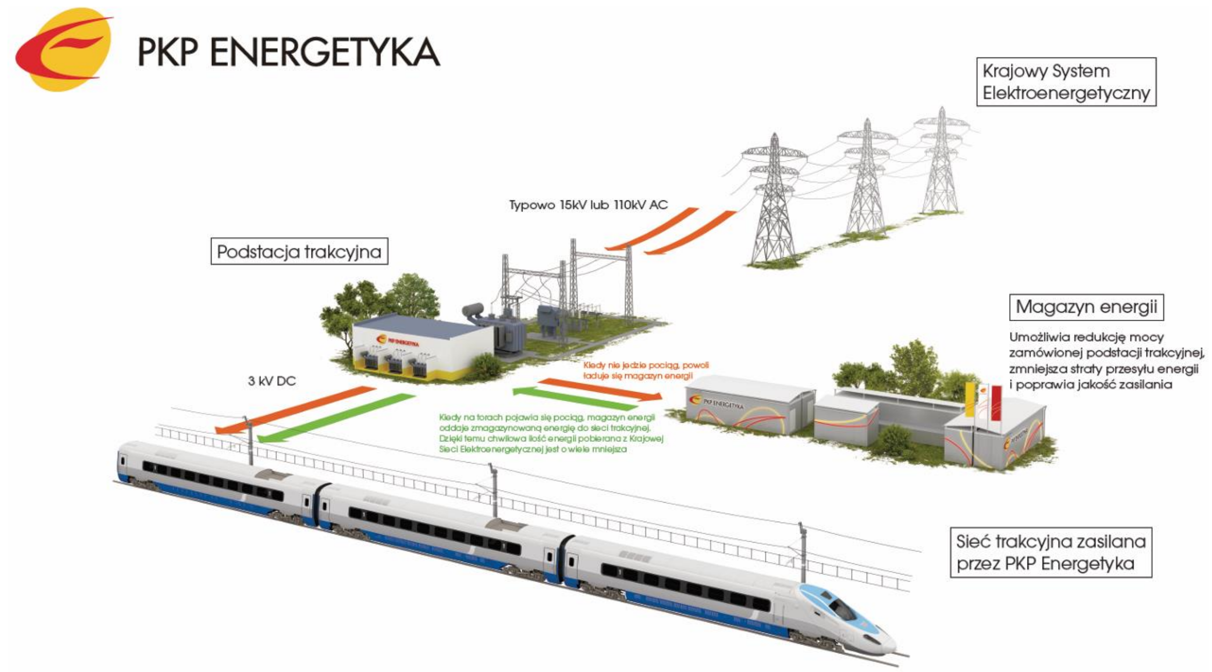

Figure 1. Scheme of energy conversion and the substation [4].

Figure 1 shows the energy conversion system used in PKP (Polish Railway Company), as detailed in the previous paragraphs. This system is divided into its individual components, each of which plays a vital role in the energy conversion process.

Essentially, a DC traction power supply system can be divided into three circuits interconnected [5]. Each of them is designed with its electrical parameters and characteristics in order to ensure successful operation of electrified railway system. Figure 2 is a schematic demonstration of a 3 kV DC power supply system.

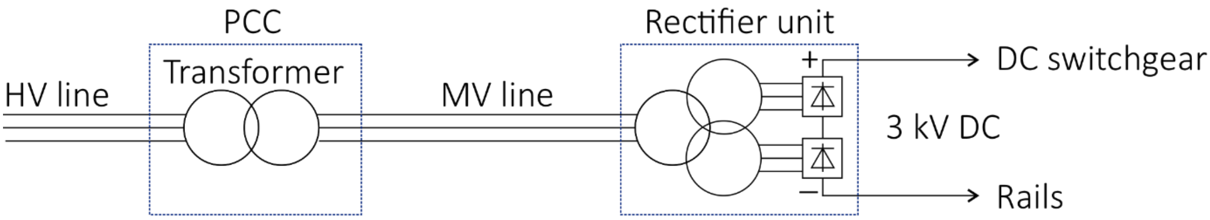

Figure 2. Demonstration of the DC power supply system.

The AC power supply system is the initial circuit in the system. The circuit's many essential parts combine to produce and distribute AC (alternating current) power. After the electricity is produced, it is moved over to a high-voltage distribution network, which minimizes energy loss while effectively transporting power over large distances. One of the examples is the Polish Railway's (PKP) traction substations, and the rated voltages in them are 15, 20, 30 or 110kV. In other countries, the rated voltages of 10, 35, 66 and 132 kV AC are used [5]. The main factors affecting the supply to the substations include the voltage level and the short-circuit power available at the power stations that are fed to the substations [6, 7]. Depending on where the traction substations are located, the distribution lines' distance between them might vary; it can be as low as 0.1 km (if the point of common connection is close to the substation) or as much as 20 km [5]. These lines are frequently built utilizing overhead conductors, subterranean cables, or even a mix of the two and their cross-section is normally from 70 to 300mm2 with different resistances for each wire as shown in Table 1.

Table 1. Resistances of wires for overhead lines [8].

Cross section [mm2]	Cable line		Overhead line AFL-6 [Ohm/km]
	Cu [Ohm/km]	Al [Ohm/km]	
70	0.258	0.443	0.434
95	0.193	0.32	0.319
120	0.153	0.253	0.234
150	0.124	0.205	0.193
185	0.099	0.164	0.156
240	0.075	0.125	0.137
300	0.060	0.1	0.121

The traction substations link to the grid at the point of common coupling (PCC), which makes it easier to move electrical energy. This power is subsequently transferred via AC transmission lines from the PCC to the traction substations, guaranteeing a consistent and dependable supply of electricity for additional processing [1]. To service and protect the AC power supply the AC switchgear if high or middle voltage is also located in the traction substations. The switchgear has circuit breakers, transformer circuit breakers, earthing switches, fuses, and measuring tools including voltage and current transducers [9]. It also contains medium- and high-voltage internal transformers. Because it enables fault isolation and equipment repair, switchgear is essential to maintaining the power supply's safety and dependability. The transformers can have a few windings and which are used for the different needs i.e. internal needs of traction substation, supply of auxiliary needs of railway line etc [10].

From the transformers the voltage is transferred to rectifier units converting AC voltage to DC. The conversion process involves several important components, including step-down and booster transformers. Step-down transformers lower the high voltage of the incoming AC power for the rectifiers, while booster transformers are used to maintain stable voltage levels along the distribution lines [11]. The important parameters to note regarding transformers are the short-circuit power of the power supply system on the HV side, rated power of the high voltage and middle voltage transformer, and the percentage of short-circuit voltage of the high voltage and middle voltage transformer. For rated voltage on the high voltage side of 110 kV, the short-circuit power on the high voltage side ranges from 1000 MVA to 1550 MVA together with the rated power of the high voltage or middle voltage transformer of 16MVA [12]. In addition, the percentage short-circuit voltage of the high voltage or middle voltage transformer ranges from 10% to 12%. Rectifiers can be 6- or 12 pulse construction (Figures 3 and 4), the last one are mainly used because of creation lower harmonics level.

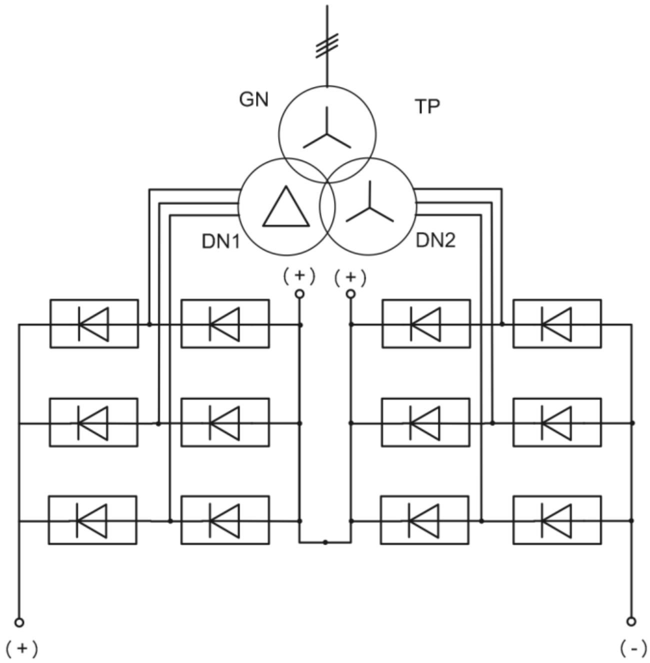

Figure 3. Structure of a 12-pulse traction rectifier (two three-phase bridges connected in series): TP – rectifier transformer, GN – upper voltage winding, DN1 – lower voltage winding connected in a delta, DN2 – lower voltage winding connected in a star [13].

Figure 4. Example of the elevation view of the PD 1700/3.3 EB rectifier [13].

Rectifiers are critical components in this circuit because of the AC power conversion into DC, which is then useable for traction systems. Rectifier transformers are installed in a variety of places, including outdoor settings at railway substations, inside environments at tram substations, AC switching stations, and specialized buildings. They can also be found underground or beneath ground level in metro substations. An example of the units of the rectifiers is PD17, PD1.7, PD16, PD12, and PK17 [12]. The number of rectifier unit can also vary from 1 to 5. These transformers altogether are intended to withstand varied loads while ensuring that the DC output fits the standards for various types of trains. Parameters of rectifier units used in Poland are shown in Table 2.

Table 2. Parameters of rectifier units used in Poland [12]

Parameters	**PD 17**	**PD 1.7**	**PD 16**	**PD 12**	**PK 17**
number of pulses	12-puls.	12-puls.	12-puls.	12-puls.	6-puls.
Rated power of the rectifier transformer [MVA]	6.4	6.3	5.85	4.4	4.4
Percentage short-circuit voltage of the rectifier transformer [%]	10	6.6	8.8	11	11
Load losses of the rectifier transformer [kW]	53.5	38	46	36	36
Rated output current of the rectifier [A]	1700	1700	1600	1200	750
Rated output voltage of the rectifier [V]	3300	3300	3300	3300	3300
Rated output power of the rectifier unit [MW]	5.61	5.61	5.28	3.96	2.475
Number of diodes connected in series in the rectifier	3	3	3	3	8
Voltage drop across the diode at rated load.	2	2	2	2	2

The rectified energy flows to smoothing reactors (cathode chokes) which are used to smooth out any ripple in the DC output, lowering voltage fluctuations that might damage performance (Figure 5). Finally, smoothing reactors improve the quality of DC power, assuring the stability and durability of traction motors. This stability is critical for sustaining the performance of electric trains, particularly during acceleration and braking.

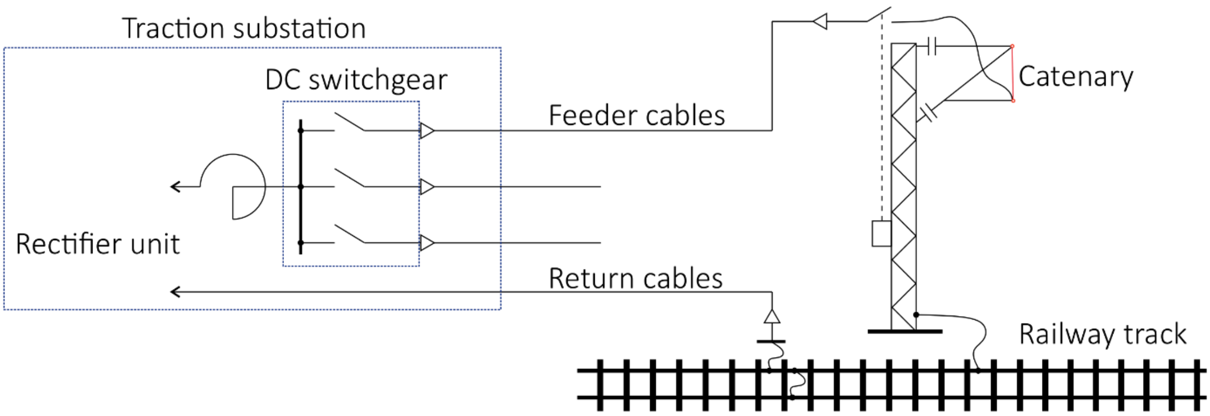

Figure 5. Demonstration of the DC traction substations.

After smoothing reactors, the rectified and smoothened voltage is delivered to DC traction switchgear shown in Figures 5 and 6 and then is delivered to catenary system. The third circuit is dedicated to the DC traction power distribution system, which sends converted DC power straight to electric trains. This circuit has numerous key components that aid in the efficient distribution of power. Switchgear is used to govern and safeguard the DC system, ensuring that it operates safely and without errors [9]. The key apparatus of DC traction switchgear are high-speed circuit brakes which are used for switching operations and perform protraction functions from overloads and short-circuits.

Figure 6. Example photo of a 3 kV DC switchgear [14].

Feeder lines provide DC electricity from substations to the overhead contact system, which powers the trains [3]. The unitary resistances of these lines, which refer to the resistance per unit length, are a crucial factor in the performance of them. Table 2 depicts the unitary resistance of the lines depending on the cross-section area and its material.

Table 3. Unitary resistances of cables depending on the cross-section area and metal [8]

Cross-section area [mm2]	Cu [Ohm/km] YKY or KYKy of 3.6/6kV	Al[Ohm/km] YAKY or YAKYy of 3.6/6kV
120	0.153	0.253
150	0.124	0.206
185	0.098	0.162
240	0.075	0.125
300	0.060	0.099
400	0.045	0.075
500	0.036	0.060
625	0.036	0.048
800	0.0236	0.0375

The overhead contact system, sometimes known as the catenary, allows trains to draw energy via a pantograph that links to above wires. The running rails also serve as the return channel for the traction current, completing the electrical circuit and allowing the trains to operate more efficiently. The catenary system is designed to reduce energy loss and assure continuous power distribution to the trains, which is critical for meeting schedule and performance [11]. The important parameter to note regarding the catenary is the unitary resistances for different catenary types. Table 4 depicts the unitary resistance of each catenary system.

Table 4. Unitary resistances of different types of catenary systems used in Poland (Sochon 2003) [8]

Catenary type	Unitary resistance of the catenary system [Ohm/km]
KB70-C	0.1230
C70-C	0.1136
C95-C	0.0985
Fe70-2C	0.0961
CuCd70-2C	0.0765
KB95-2C, YKB95-2C	0.0705
C95-2C, YC95-2C, YpC95-2C	0.0662
C150-C150, YC150-C150	0.0642
C120-2C, YC1202C, YpC120-2C, YzC120-2C, YSC120-2C, Yws120-2C	0.0613
C120-2C150, YC120-2C150	0.0470
2C120-2C, 2C120-2C-1, 2C120-2C-2	0.0440
C150-2C150	0.0435

These three circuits work together to produce consistent and efficient traction power for electric trains. The AC grid provides high-voltage electricity, which is converted to useable DC by substations, and the distribution system guarantees that this power is successfully delivered to the trains. This well-coordinated system enables electric trains to accelerate quickly, sustain high speeds, and brake efficiently, highlighting the benefits of electric traction technology in modern rail transit. The incorporation of new technologies into monitoring and control systems improves the overall efficiency and safety of the traction power supply system.

3. Key analyses performed by simulator

To ensure reliable and efficient traction power for electric trains, each of the three calculations, substation performance, traction system voltage and current distribution, and short-circuit analysis, plays a crucial role [15].

3.1. Substation analysis

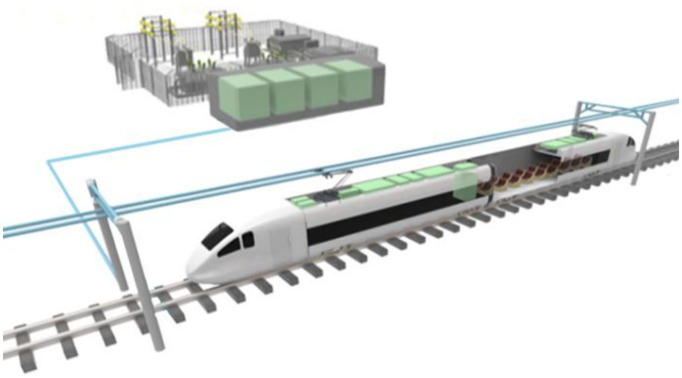

Figure 7. Schematic representation of a railway substation layout [16].

Figure 7 depicts the schematic representation of a railway substation. The substation performance analysis gives information on the voltage output, current handling capacity, and voltage drop over the power lines. Key characteristics such as the traction substation's no-load voltage, the relative voltage drop in the MV line, and the internal resistance of the rectifier units are crucial in determining how effectively the substation maintains voltage under changing load situations. Maintaining a stable voltage is critical for avoiding performance concerns in electric trains, such as slow acceleration or irregular power supply.

The short-circuit power calculation measures the substation's capacity to manage fault conditions. This is critical for ensuring that the substation can resist and clear faults without causing major damage or disruption to service. A high short-circuit power capability indicates that the substation can handle greater faults while continuing to deliver dependable power under typical operating conditions.

The internal resistance of all rectifier devices gives insight into energy losses within the substation. Lower internal resistance translates to less power loss and more efficiency in transferring electrical power for use by trains.

3.2. Traction system voltage and current distribution

Voltage calculations at various locations along the track, such as at the pantograph, are crucial for ensuring that the electric train receives enough voltage to function properly [17]. Voltage drops throughout the cable might result in lower performance and dependability. The analysis aids in the design of systems that reduce voltage drops, allowing trains to operate effectively over extended distances.

The current distribution at the section's beginning and ending indicates how effectively the power is balanced between the two supply sites. Efficient current distribution guarantees that neither end is overburdened, and the power supply is steady. In a two-sided system, balanced distribution helps prevent excessive current draw from a single supply point, which can cause overheating and failure [18].

By analyzing how the current changes with distance, engineers can design better power supply systems that optimize load sharing and minimize the impact of distance on performance. This leads to more reliable operations and better power utilization.

3.3. Short-circuit analysis

The short-circuit analysis offers critical information regarding the maximum short-circuit current and how it is distributed across the section. This information is critical for constructing protective devices and ensuring that the system can handle faults safely [5]. The ability to isolate problems promptly and securely is critical for limiting damage and guaranteeing uninterrupted power supply.

Understanding short-circuit levels is useful for constructing circuit breakers and other protective devices to handle high fault currents. Proper protection guarantees that the system recovers rapidly from errors, avoiding long-term interruptions or damage.

Short-circuit power analysis is also useful in developing systems that can resist and clear faults effectively, hence improving the overall safety and reliability of the traction power system. Effective fault management eliminates cascade failures and guarantees that the power supply network operates continuously.

4. Implementing the practical components of the program

Figures 8 and 9 illustrate the conventional design of the laboratory stand.

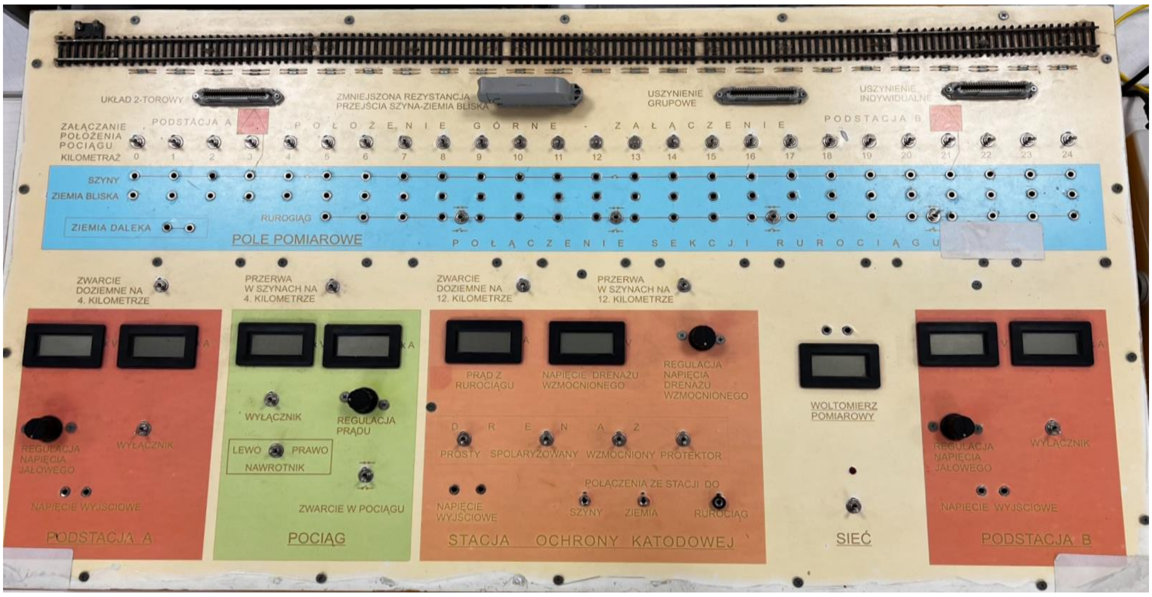

Figure 8. A picture of an already existing conventional laboratory stand.

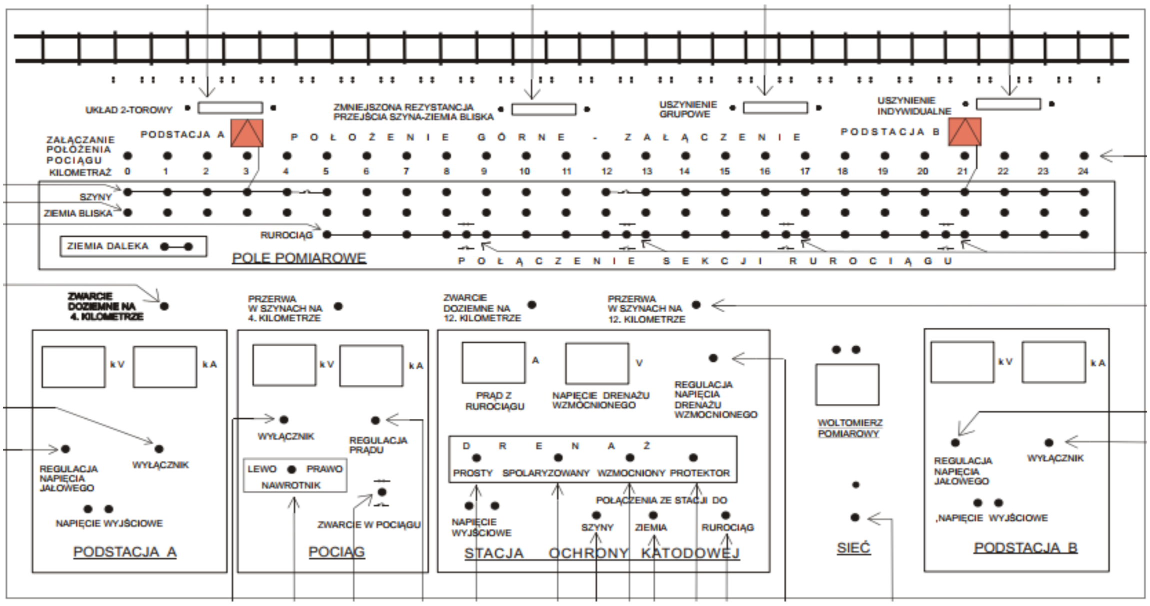

Figure 9. A scheme of an already existing laboratory stand [19].

Figures 8 and 9 depict the laboratory setup that is used in the already existing conventional laboratory and it includes a track for a locomotive, along with measuring and control components. Models A and B of the supply substation are positioned on the left and right sides at the bottom. Below these models, there are various parameters that can be measured and controlled. This simulator is relatively straightforward, capable of analyzing voltages on the pantograph and detecting short circuits; however, it is somewhat outdated and tends to malfunction occasionally. In contrast, the newly developed virtual simulator presented in this thesis allows for more precise simulations, accommodating a variety of parameters such as different cable types, distances, and more.

4.1. Selection of a programming language

Figure 10: Python logo [20].

For the development of this simulator, Python has been selected as the programming language. This choice is substantiated by several compelling factors

Firstly, ease of learning. Python's simple syntax and readability make it an excellent choice for new and seasoned programmers. This accessibility enables quick development and iterative testing, both of which are essential in a research setting.

Secondly, the cross-platform compatibility. Python's intrinsic interoperability with many operating, specifically Windows, macOS, and Linux, which ensures that the simulator may be deployed in a variety of scenarios, boosting its utility and reach.

Another factor is the extensive libraries. The availability of substantial libraries such as Tkinter, PyQt, and Kivy enables the development of strong graphical user interfaces (GUIs). These libraries improve user interaction with the simulator, making it more understandable and useful for analysis.

Lastly, the community support. The robust and active Python community offers a multitude of resources, such as documentation, forums, and collaboration possibilities. This support network is crucial for diagnosing and improving the simulator, as well as ensuring that software development best practices are followed.

4.2. Main window of the simulator

Figure 11 depicts the very first part of the program and it is built by creating a class ‘Application’ in the program code as shown below

```python
class Application:
    def __init__(self):
        self.window = tk.Tk()
        self.window.title("Railway Electrification Calculation Simulator")
        self.window.geometry("480x580")
        self.transport_type = tk.StringVar(value="Mode of transportation")
        self.type_of_calculation = tk.StringVar(value="Type of calculation")

        script_dir = os.path.dirname(os.path.abspath(__file__))
        ico_path = os.path.join(script_dir, "images/train.ico")
        self.window.iconbitmap(default=ico_path)
        self.create_first_page()
```

Figure 11. Part of the code script of the first window.

It sets the size of the window in terms of the size of the resolution and creates the parameter drop down menu named accordingly. In addition, the ‘iconbitmap’ command is used to set the icon of the program itself.

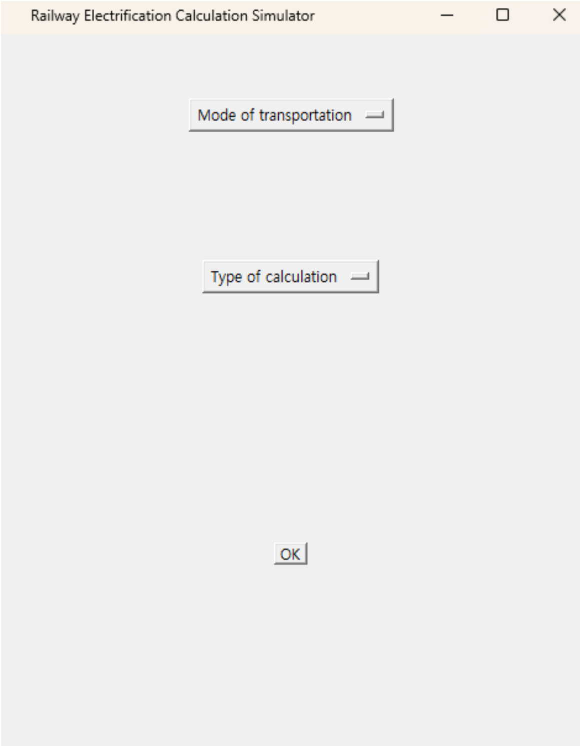

Figure 12. First window of the program.

Figure 12 is the initial window that appears when the program is launched presents users with the option to select their 'Mode of Transportation' and 'Type of Calculation'. This is provided by a dropdown menu, which displays the available options when clicked.

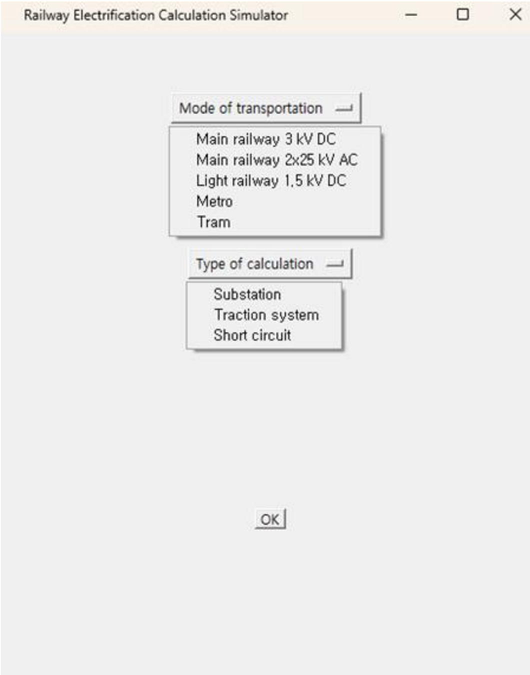

Figure 13. Demonstration of the drop-down menus on the first window.

Once the user has chosen their preferred mode of transportation and type of calculation, clicking the 'OK' button will take them to the main window corresponding to their selected options as shown in Figure 13. Only the 'Main Railway 3 kV DC' option is currently functional and selecting any other options will result in an error message being displayed.

```
if self.t (variable) window: TransportPageForTrain )C" and self.type_of_calculation.get() == "Substation":
    self.window = TransportPageForTrain(self.type_of_calculation.get())
elif self.transport_type.get() == "Main railway 3 kV DC" and self.type_of_calculation.get() == "Traction system":
    self.window = railwaytractionpage(self.type_of_calculation.get())
elif self.transport_type.get() == "Main railway 3 kV DC" and self.type_of_calculation.get() == "Short circuit":
    self.window = railwayshortcircuitpage(self.type_of_calculation.get())
```

Figure 14. Function script used to navigate to the second window of the program.

Figure 14 depicts the function used to navigate the user to the appropriate window after selecting the mode of the transportation and the type of calculation. It determines what parameters are selected and passed through and runs the class accordingly.

4.3. Main railway 3 kV DC substation simulator

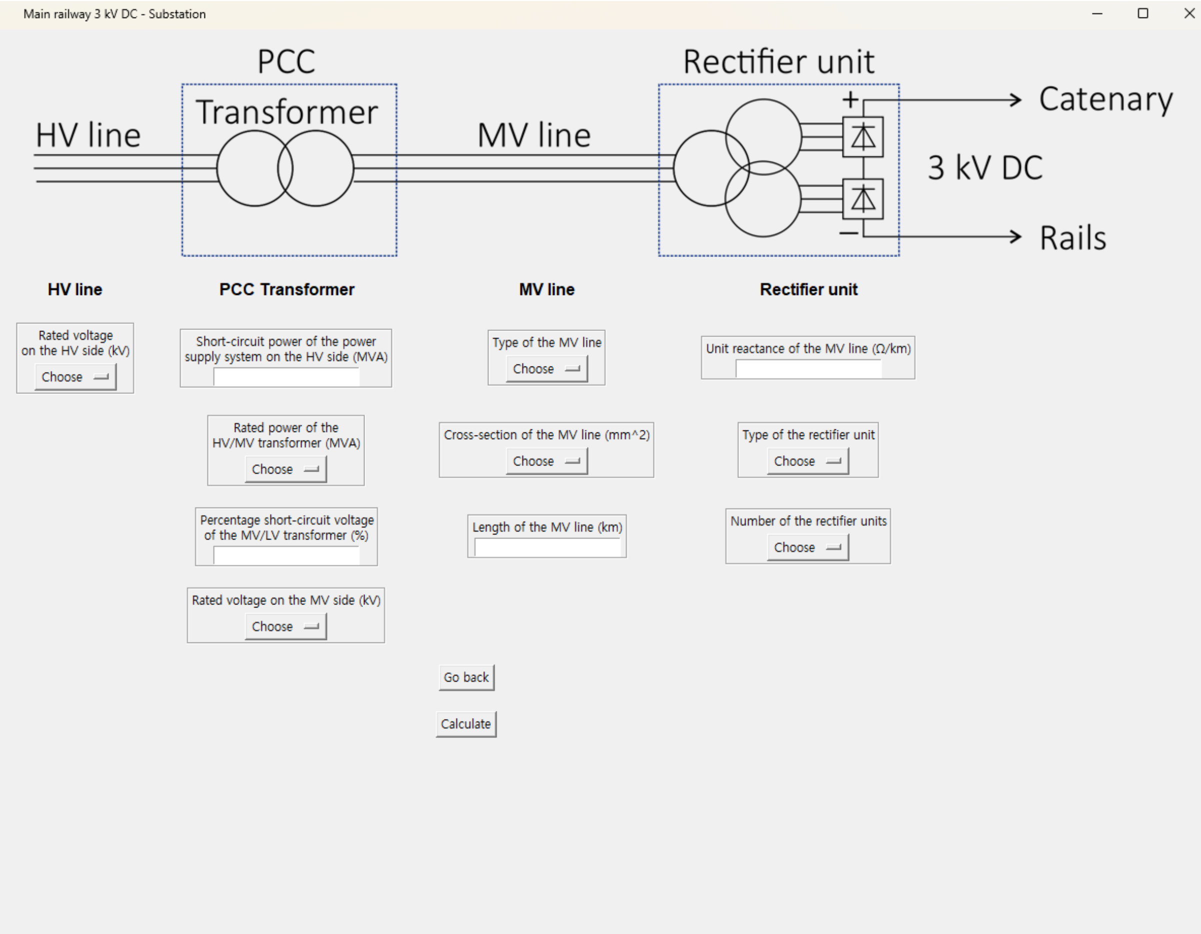

Figure 15. Main window of the substation calculation simulation.

After selecting 'Main Railway 3 kV DC' and 'Substation', a window similar to the one displayed above will appear as shown in Figure 15. This serves as the main window for the substation calculation. At the top, there is a schematic diagram that illustrates the simulation model. The window is divided into four sections: 'HV Line', 'PCC Transformer', 'MV Line', and 'Rectifier Unit'. Beneath each section, the user can input their values into designated parameters. These parameters are strategically placed to enhance the program's comprehensibility and user-friendliness. Once the user has inputted the required parameters, the calculation can be initiated by clicking the 'Calculate' button. The necessary data for these parameters should be provided by the professor overseeing this laboratory experiment.

```python
self.canvas = tk.Canvas(self.window, width=1200, height=230)
self.canvas.grid(row=1, column=0, rowspan=2, columnspan=15)

script_dir = os.path.dirname(os.path.abspath(__file__))
img_path = os.path.join(script_dir, "images/TS.png")

train_img = Image.open(img_path)
new_width = train_img.width // 1.8
new_height = train_img.height // 1.8
train_img_resized = train_img.resize((int(new_width), int(new_height)))
train_img_tk = ImageTk.PhotoImage(train_img_resized)
self.train_image = self.canvas.create_image(600, 120, image=train_img_tk)

global _image
_image = train_img_tk
```

Figure 16. Part of the second window function which displays the image of DC power supply.

Figure 16 depicts the very first part of the function that creates the second window as shown in the Figure 10. It firstly, creates a canvas to create space for the image of DC power supply to be displayed. And then, it gets the directory of the current script file and joins the directory of the script file with the image filename. This is called using the absolute path and it allows the image to be loaded on a different device with different directory. In addition, the image is stored in a global variable to prevent it from being garbage collected.

```python
tk.Label(self.window, text="HV line", font=("Helvetica", 12, "bold")).grid(row=3, column=0, padx=10, pady=10)
frame1 = tk.Frame(self.window, bd=2, relief="groove")
frame1.grid(row=4, column=0, padx=10, pady=10)
label1 = tk.Label(frame1, text="Rated voltage\non the HV side (kV)")
label1.pack()
self.parameter_1.set("Choose")
option_menu1 = tk.OptionMenu(frame1, self.parameter_1, "110")
option_menu1.pack()
```

Figure 17. Part of the second window function for creating the parameter fields.

Figure 17 depicts the part of the function for creating the parameter fields. It uses tk.Label to create texts and uses tk.Frame to create the frame to make a frame around the parameter field. The tk.OptionMenu is used to create a drop down menu for the parameters to be selected by the user.

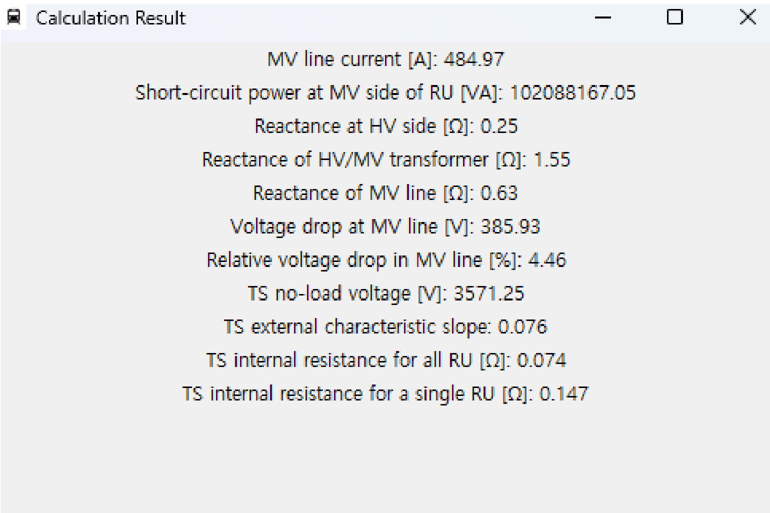

Figure 18. Calculation result window of the substation simulation.

Figure 18 demonstrates the outcome when the 'Calculate' button is pressed. As illustrated, the calculated results are displayed for the following parameters:

- Middle Voltage (MV) Line Current
- Short-Circuit Power at the Middle Voltage Side of the Rectifier Unit
- Reactance at the High Voltage (HV) Side
- Reactance of the HV/MV Transformer
- Reactance of the MV Line
- Voltage Drop at the MV Line
- Relative Voltage Drop in the MV Line
- Traction Substation (TS) No-Load Voltage
- TS External Characteristic Slope
- TS Internal Resistance for All Rectifier Units
- TS Internal Resistance for a Single Rectifier Unit

This is done by using the calculation algorithm. As shown in Figure 19, the initial step is to collect the selected parameters from the user and set the appropriate values for the calculation.

```
parameter_9_value = self.parameter_9.get()
if parameter_9_value == "PD17":
    parameter_9_1 = 6400000
elif parameter_9_value == "PD1.7":
    parameter_9_1 = 6300000
elif parameter_9_value == "PD16":
    parameter_9_1 = 5850000
else:
    parameter_9_1 = 4400000
parameter_10_value = float(self.parameter_10.get())
parameter_5_value = float(self.parameter_5.get())
result_a = [(parameter_9_1 * parameter_10_value) / (math.sqrt(3) * (parameter_5_value * 1000))]
return result_a
```

Figure 19. Part of the calculation script for calculation for substation simulation.

By using 'if' function, the program sets the value needed for the calculation depending on the parameter chosen by the user. Some of the parameters can be directly used without this process when the parameters chosen are the actual values needed for the calculation such as the 'parameter_10_value' and the 'parameter_5_value' in Figure 19. Then, the values collected are used in the equations as shown in Figure 19 above to calculate the result and finally it returns the calculated value.

```
#Calculate button
tk.Button(self.window, text="Calculate", command=self.show_result).place(x=550, y=640)
```

Figure 20. Script line for the 'calculate' button.

Figure 20 shows the line that allows the calculate button to call the function 'show_result' once it is pressed.

```
def show_result(self):
    result_window = tk.Toplevel(self.window)
    result_window.title("Calculation Result")
    result_window.geometry("500x300")
```

Figure 21. Part of the script of calculation result window.

Once the show_result function is called, it creates another window called ‘Calculation result’ as shown in Figure 21.

```
result_a = [round(num, 2) for num in self.calculation_a()]
result_a_str = ', '.join(map(str, result_a))
tk.Label(result_window, text=f"MV line current [A]: {result_a_str}").pack()
```

Figure 22. Part of the script for displaying the results,

The results are then called from the calculation functions and are displayed by using ‘tk.Label’ as shown in Figure 22.

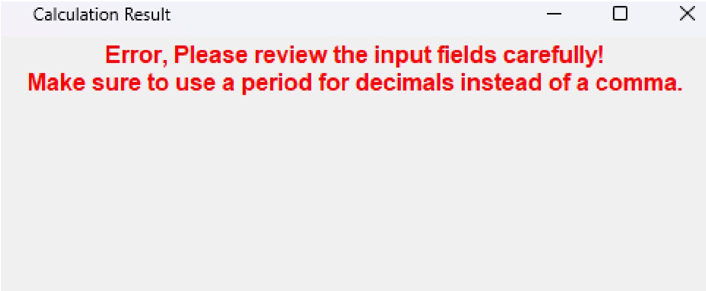

Figure 23. Result of an error window.

Figure 23 demonstrates what happens when the calculation cannot be completed due to incomplete or wrong input values. And this is done by simply adding the lines shown in the Figure below.

```
error_message = tk.Label(result_window, text="Error, Please review the input fields carefully!
error_message.pack()
```

Figure 24. Part of the script of the result of an error window.

Similar windows pop up for the rest of the different calculations performed when an error occurs.

4.4. Main window of the simulator

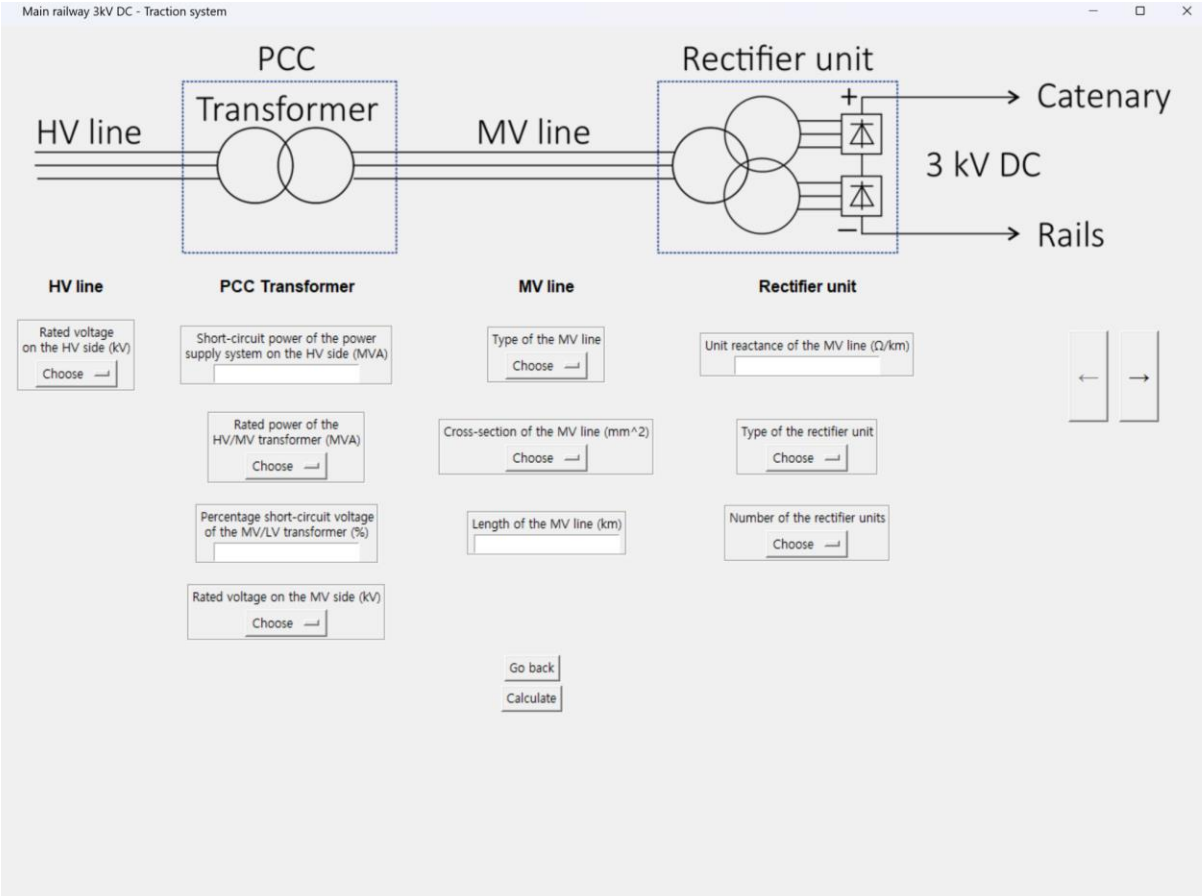

Figure 25. Main window of the traction system calculation simulation.

Upon selecting 'Traction System' as the calculation type on the initial window, the window depicted in the Figure appears as shown in Figure 25. This window closely resembles the one that appears when the 'Substation' calculation is selected. However, it includes additional parameters that must be entered, as indicated by the arrows on the right side of the window.

```
self.arrow_button = tk.Button(self.window, text="→", command=self.show_new_parameters, height=3, font=('Helvetica', '16'))
self.arrow_button.place(x=1110, y=300)  # Example coordinates

self.arrow_button1 = tk.Button(self.window, text="←", command=self.untoggle_parameters, height=3, font=('Helvetica', '16'))
self.arrow_button1.place(x=1060, y=300)  # Example coordinates
self.arrow_button1.config(state="disabled")
```

Figure 26. Part of the script that creates the arrows for the second window.

As shown in Figure 26, this is done by simply adding the buttons by using ‘tk.Button’ function and setting it to call the function for displaying new parameter fields when it is pressed. By clicking the right arrow button, the user can access more parameter input fields, as illustrated in the Figure below.

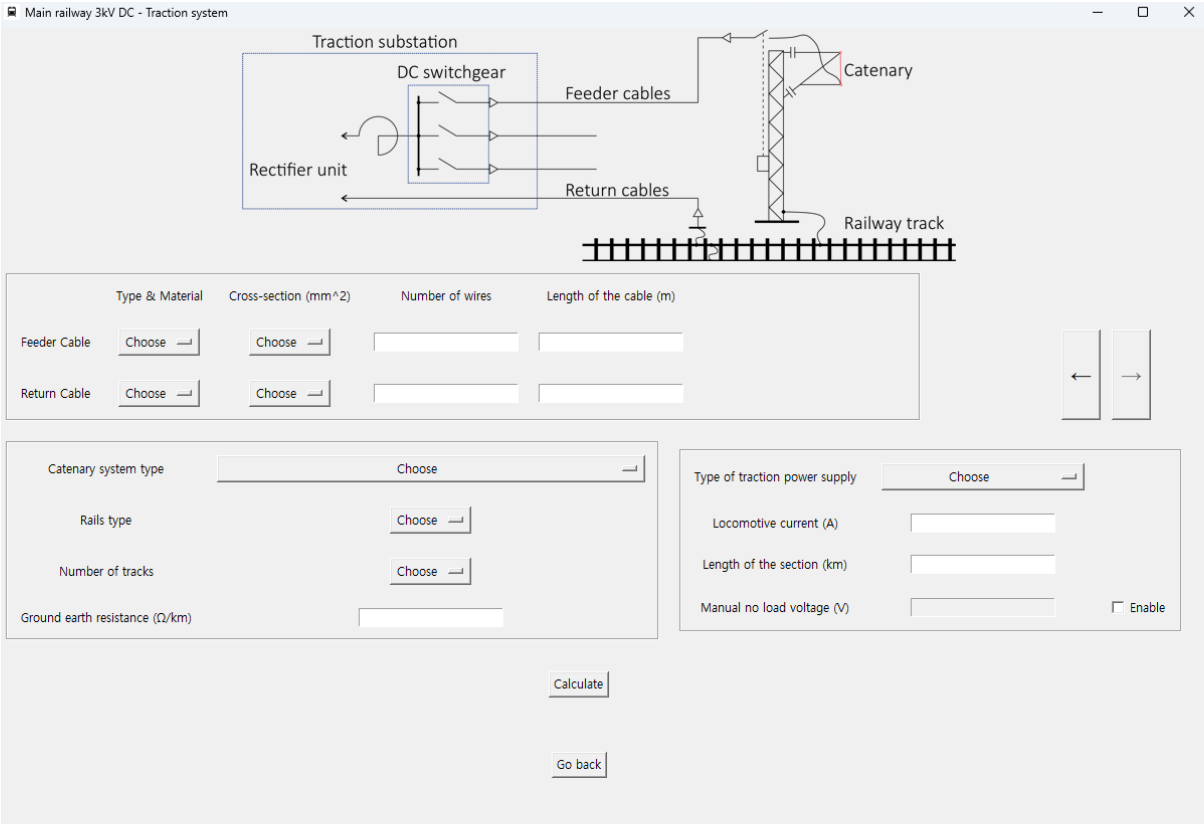

Figure 27. Second window of the traction system calculation simulation.

The window shown in Figure 27 is displayed when the right arrow is clicked. At the top, users can specify the type and material of the feeder and return cables, as well as their cross-sectional area, number of wires, and length. Below this section, options are available to select the type of catenary system, type of rails, number of tracks, and ground earth resistance. Adjacent to these options, users can choose the type of traction power supply and input fields for locomotive current and section length.

The no-load voltage is automatically calculated based on the parameters selected by the user; however, for added convenience, there is an option to manually input the no-load voltage. This input field is initially disabled, but users can click the enable button to make it accessible and enter their desired no-load voltage. This manual entry will override the automatically calculated no-load value, and the program will use the user-specified value for subsequent calculations.

```
self.new_parameter_13 = tk.StringVar()
self.new_entry6 = tk.Entry(self.combined_frame, textvariable=self.new_parameter_13, state='disabled')
self.new_entry6.grid(row=3, column=1, padx=10, pady=10)
```

Figure 28. Part of the script to create a new field for entering no-load voltage.

This is done by creating another parameter and creating the entry field by using ‘tk.StringVar’ and ‘tk.Entry’. It is initially set as ‘state=disabled’ as shown in Figure 28.

```
self.tick_button_var = tk.BooleanVar()
self.tick_button = tk.Checkbutton(self.combined_frame, text="Enable", variable=self.tick_button_var, command=self.manual_no_load_voltage)
self.tick_button.grid(row=3, column=2, padx=10, pady=10)  # Adjust grid position as needed
```

Figure 29. Part of the script to forward the no-load voltage value to be used in the calculation.

The button to enable the field is created by ‘tk.BooleanVar’ and once it is enabled, the ‘manual_no_load_voltage’ function is called as shown in Figure 29 by using ‘command=self.manual_no_load_voltage’.

```python
result_e, _ = self.calculation_e()

if self.tick_button_var.get():
    u_oca = float(self.new_parameter_13.get())
else:
    u_oca = float(result_e[0])
```

Figure 30. Part of the script to check if the manual no-load voltage value is present.

After that, in the calculation algorithm, the lines to check if the button is checked are added as shown in Figure 30. If it is checked then it assigns the value from the entry box to the appropriate parameter value and it is used for the calculation. It is also worth noting that as all the values are initially strings, it is necessary to change them to float for the calculations to be successful by using ‘float’ function.

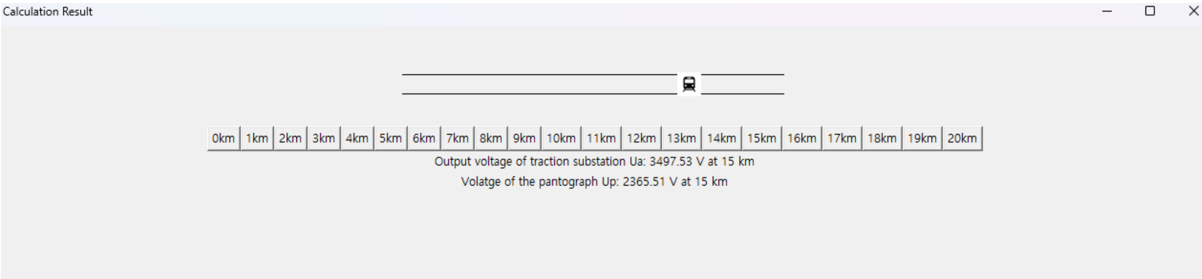

Figure 31. Calculation result window of the traction system one-sided calculation.

Figure 31 displays the calculation result window for a one-sided traction power supply, which appears after pressing the 'Calculate' button. Buttons are created, ranging from 0 to the value entered by the user (in this case, 20 km), representing the localization of the locomotive. Each successful press on a button prints the resulting calculations underneath it. In the Figure above, the 15 km button has been pressed, displaying the pantograph voltage and traction substation output voltage at 15 km of locomotive localization. To help the user visualize the locomotive's position, an image of the train moves according to the localization chosen by the user.

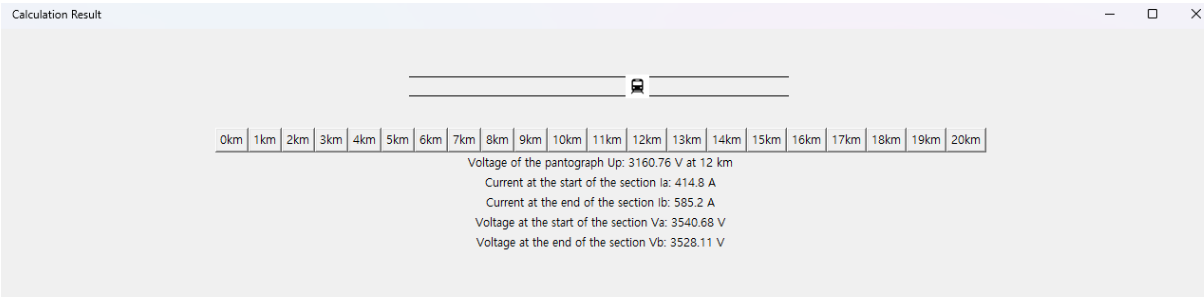

Figure 32. Calculation result window of the traction system two-sided calculation.

When the selected type of traction power supply is 'two-sided', a window similar to the one depicted in Figure 32 appears. This window displays the pantograph voltage, voltage at the start of the section, at the end of the section, current at the start of the section, and current at the end of the section, based on the locomotive localization chosen by the user.

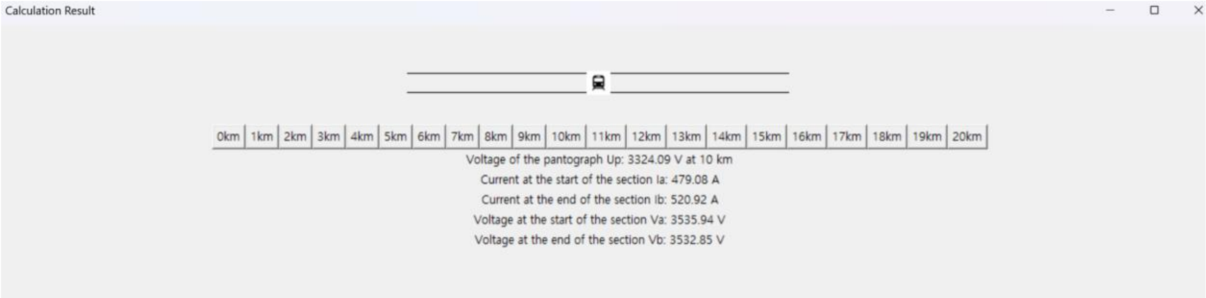

Figure 33. Calculation result window of the traction system two-sided sectioning cabin calculation.

A similar window appears when the selected type of traction power supply is 'two-sided with sectioning cabin' as shown in Figure 33. The key distinction is the inclusion of two additional results: the voltage at the start of the section and the voltage at the end of the section. All other functionalities remain unchanged, including the movement of the train on the track corresponding to the button pressed at that moment.

```
length_of_section, *_ = self.parameter_collected()
length_of_section_for_button = int(length_of_section) + 1

self.canvas = tk.Canvas(simulation_window, width=500, height=100)
self.canvas.pack()
self.canvas.create_line(50, 50, 450, 50)  # Top rail
self.canvas.create_line(50, 70, 450, 70)  # Bottom rail

script_dir = os.path.dirname(os.path.abspath(__file__))
img_path = os.path.join(script_dir, "images/train.png")
train_img = Image.open(img_path)
new_width = train_img.width // 8
new_height = train_img.height // 8
train_img_resized = train_img.resize((new_width, new_height))
self.train_img_tk = ImageTk.PhotoImage(train_img_resized)
self.train_image = self.canvas.create_image(50, 60, image=self.train_img_tk)
```

Figure 34. Part of the calculation result window of traction system.

In order to create the result window of the traction system calculation, it is necessary to check the parameters inputted for the length of the section by the user. It is done by using the 'length_of_section = self.parameter_collected' line shown in Figure 34 and it calls the selected value by the user. This is then used to create the buttons accordingly to ensure that the buttons are created for the range of the length of the section that the user wants to calculate. After that the 'canvas' function is used to create the representation of top and bottom rail and the image is called also by using the absolute path.

```
def move_train_to(self, km):
    length_of_section, *_ = self.parameter_collected()
    aaa = (400/length_of_section) * km
    x = 50 + aaa # Calculate the x-coordinate for the given distance
    self.canvas.coords(self.train_image, x, 60)  # Move the train image to the new position
```

Figure 35. Part of the script to simulate the train.

When the button is pressed the function 'move_train_to' is called as shown in Figure 35. The function calls the length of section value chosen by the user and uses it to calculate the x-coordinate for the given distance.

4.5. Main railway 3 kV DC short-circuit calculation simulator

When the chosen calculation type is ‘short-circuit’, the initial window that appears is nearly identical to the one used for traction system calculations, with minor modifications to the second window of parameters as shown in Figure 36.

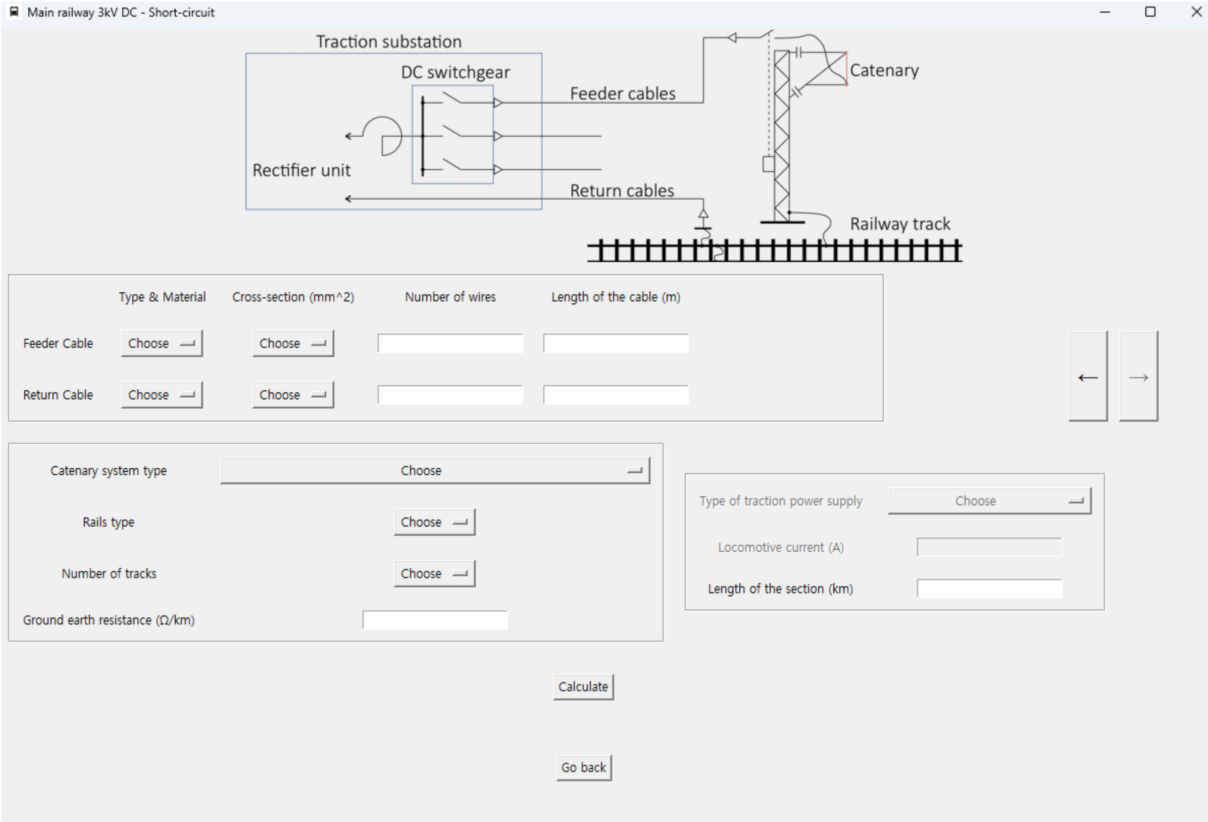

Figure 36. Main window of the short-circuit simulation.

As indicated, the parameters that need to be entered are identical until the user reaches the sections for the type of traction power supply and locomotive current. These two options are disabled, as they are not applicable for the short circuit calculation. After successfully inputting all necessary values, the user can proceed by pressing the 'Calculate' button to initiate the calculation.

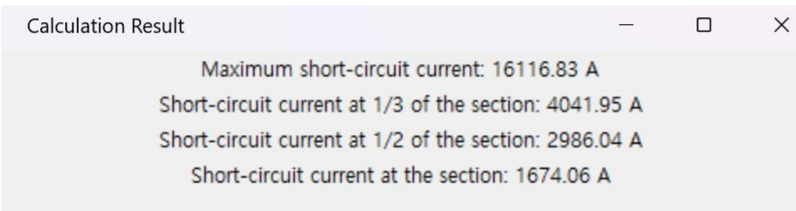

Figure 37. Calculation result window of the short-circuit simulation.

Figure 37 illustrates the result that appears upon pressing the 'Calculate' button. The window displays four key results:

- Maximum short-circuits current
- Short-circuit current at one-third of the section
- Short-circuit current at the midpoint of the section
- Short-circuit current at the end of the section

5. Execution of an exemplary simulation calculation

To demonstrate that the current program is functioning properly, example calculations have been conducted.

Below are the parameters that are used for the calculation:

- Rated voltage on the HV side (kV): **110**
- Short-circuit power of the power supply system on the HV side (MVA): **1000**
- Rated power of the HV/MV transformer (MVA): **16**
- Percentage short-circuit voltage of the MV/LV transformer (%): **11**
- Rated voltage on the MV side (KV): **15**
- Type of the MV line: **Overhead AFL-6**
- Cross-section of the MV line (mm^2): **3x240**
- Length of the MV line (km): **1.75**
- Unit reactance of the MV line (Ω/km): **0.36**
- Type of the rectifier unit: **PD 1.7**
- Number of the rectifier units: **2**

5.1. Demonstration of the substation calculation simulation

The following is the procedure for the substation simulation:

1) Choose ‘Main railway 3 kV DC’ and ‘Substation’ in the first window.
2) For each section of the parameters (HV line, PCC Transformer, MV line, Rectifier unit) choose or input the desired parameters.
3) Ensure that you use a period instead of a comma for decimal points and review all the parameters to ensure they are correctly inputted.
4) Press the calculate button at the bottom of the window to proceed to the calculation results.
5) Note: Using a comma will trigger an error window that may cause the program to crash.

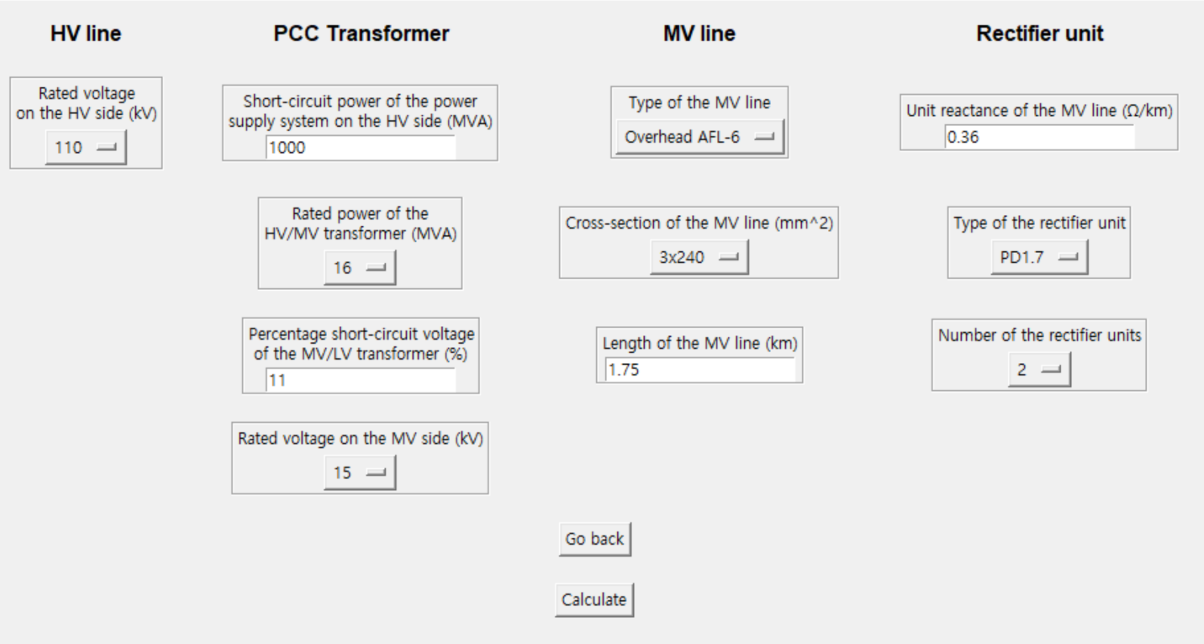

Figure 38. Parameters that are inputted for the substation calculation.

Figure 38 illustrates the appearance of the program after all values have been entered.

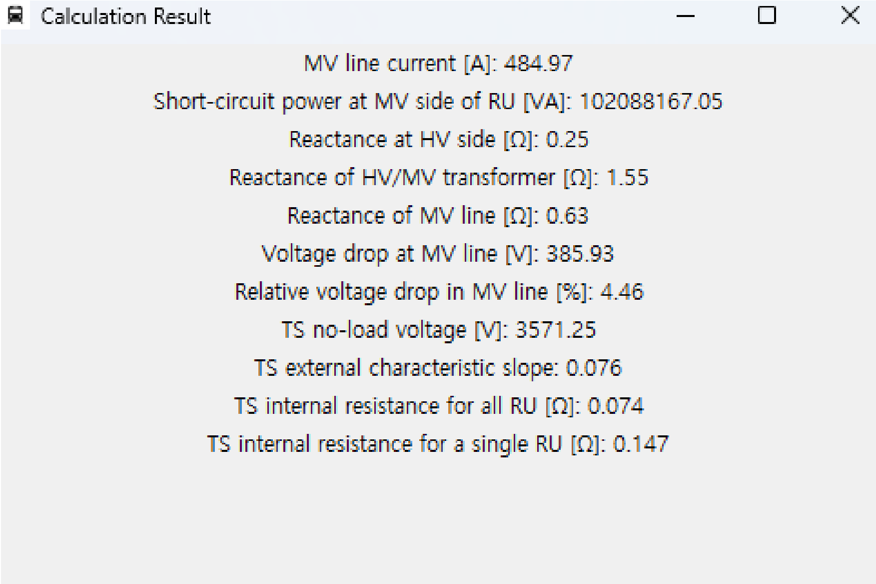

Figure 39. Calculation result of the sample substation calculation.

The result of the substation calculation is shown in Figure 39 and it is as follows.

- Middle Voltage (MV) Line Current (A): **484.97**
- Short-Circuit Power at the MV Side of the Rectifier Unit (VA): **102088167.05**
- Reactance at the High Voltage (HV) Side (Ω): **0.25**
- Reactance of the HV/MV Transformer (Ω): **1.55**
- Reactance of the MV Line (Ω): **0.63**
- Voltage Drop at the MV Line (V): **385.93**
- Relative Voltage Drop in the MV Line (%): **4.46**
- Traction Substation (TS) No-Load Voltage (V): **3571.25**
- TS External Characteristic Slope (r.u.): **0.076**
- TS Internal Resistance for All Rectifier Units (Ω): **0.074**
- TS Internal Resistance for a Single Rectifier Unit (Ω): **0.147**

The calculated Middle Voltage (MV) Line Current is 484.97 A, which indicates the current flowing through the MV line under the specified load conditions. This value is crucial for determining the appropriate sizing of cables and other components in the system to ensure they can safely handle this current without overheating or excessive energy loss.

The Short-Circuit Power at the MV Side of the Rectifier Unit, calculated to be 102,088,167.05 VA, reflects the potential power available during a short-circuit event. This high value is expected, as substations are designed to handle significant power levels to ensure the safety and protection of the system. Adequate protective measures, such as circuit breakers, must be in place to manage these levels of power.

The Reactance at the High Voltage (HV) Side of 0.25 Ω and the Reactance of the HV/MV Transformer at 1.55 Ω are important parameters in the analysis of the system's impedance. The reactance contributes to the overall impedance of the system, influencing the voltage drop and the stability of the system during load variations. Additionally, the Reactance of the MV Line, calculated to be 0.63 Ω, also plays a critical role in determining the overall impedance, which directly impacts the voltage regulation of the substation.

The Voltage Drop at the MV Line is 385.93 V, which corresponds to a Relative Voltage Drop of 4.46%. This percentage is within the acceptable range for most power distribution systems, indicating that the voltage drop along the MV line is not excessive. However, it must be closely monitored to ensure that it remains within the permissible limits to avoid undervoltage issues at the load end.

The Traction Substation (TS) No-Load Voltage is calculated to be 3,571.25 V. This represents the voltage level at the substation when no load is connected, providing a baseline for further analysis of the voltage behaviour under different load conditions. This value is essential for understanding how the substation will perform as load increases.

The External Characteristic Slope of the TS, which is 0.076, reflects the substation's voltage regulation characteristic as the load changes. A low slope value indicates good voltage stability, meaning that the substation will experience minimal voltage fluctuations as the load varies.

The TS Internal Resistance for all rectifier units combined is 0.074 Ω, while for a single rectifier unit, it is 0.147 Ω. These resistances are indicative of the losses within the rectifier units. The lower the internal resistance, the more efficient the rectifier units are, minimizing energy losses during the conversion process. The difference between the combined and single rectifier unit resistances also provides insight into the impact of scaling the system, with combined units showing better overall performance due to the parallel operation.

5.2. Demonstration of the traction system simulation

The same parameters are used as the substation calculation and as there are more parameters needed to be added in the traction system calculation, below are the additional parameters that are used.

- Catenary system type: **C120-2C, YC1202C, YpC120-2C, YzC120-2C, YSC120-2C, Yws120-2C**
- Rails type: **S-60**
- Number of tracks: **Single-track**
- Ground earth resistance (Ω/km): **0.46**
- Type of traction power supply: **One-sided, two-sided, and two sided with sectioning cabin (All 3 calculations are performed)**
- Locomotive current (A): **1000**
- Length of the section (km): **20**

For feeder cable:

- Material: **Aluminium**
- Type: **YAKY**
- Cross-section (mm^2): **500**
- Number of wires: **2**
- Length of the cable (m): **350**

For feeder cable:

- Material: **Aluminium**
- Type: **YAKY**
- Cross-section (mm^2): **240**
- Number of wires: **6**
- Length of the cable (m): **350**

The following is the procedure for the substation simulation:

1) Choose ‘Main railway 3 kV DC’ and ‘traction system’ in the first window.
2) For each section of the parameters (HV line, PCC Transformer, MV line, Rectifier unit) choose or input the desired parameters.
3) Click the right arrow on the right side to access the second page for additional parameter input.
4) As shown in the Figure 21, input the rest of the desired parameters.
5) Ensure that you use a period instead of a comma for decimal points and review all the parameters to ensure they are correctly inputted.
6) Press the calculate button at the bottom of the window to proceed to the calculation results.
7) As shown in the Figures 14, 15 and 16, a simulation window will pop up.
8) Click the km buttons (locomotive location) to view the calculation results for the selected locomotive location.
9) Change the type of traction power supply to see the results for different traction power supply types.
10) Note: Using a comma will trigger an error window that may cause the program to crash.

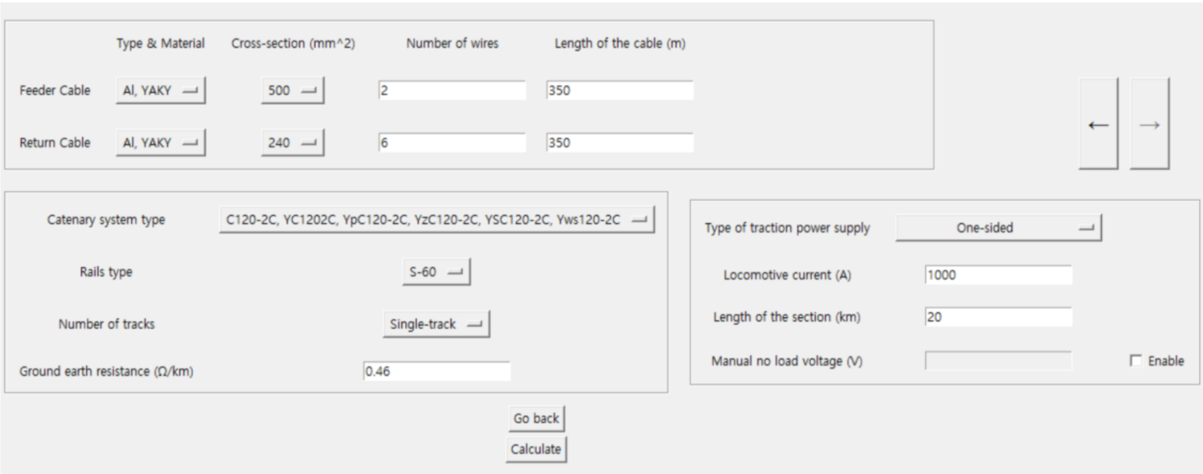

Figure 40. Additional window for new parameters for traction system calculation.

Figure 40 demonstrates the second window of the traction system parameter window with additional parameters are filled in.

Table 5. Calculation result of one-sided power supply system.

l [km]	0	2	4	6	8	10	12	14	16	18	20
Ua [V]	3497.53	3497.53	3497.53	3497.53	3497.53	3497.53	3497.53	3497.53	3497.53	3497.53	3497.53
Up [V]	3446.15	3302.07	3157.98	3013.89	2869.81	2725.72	2581.63	2437.55	2293.46	2149.38	2005.29

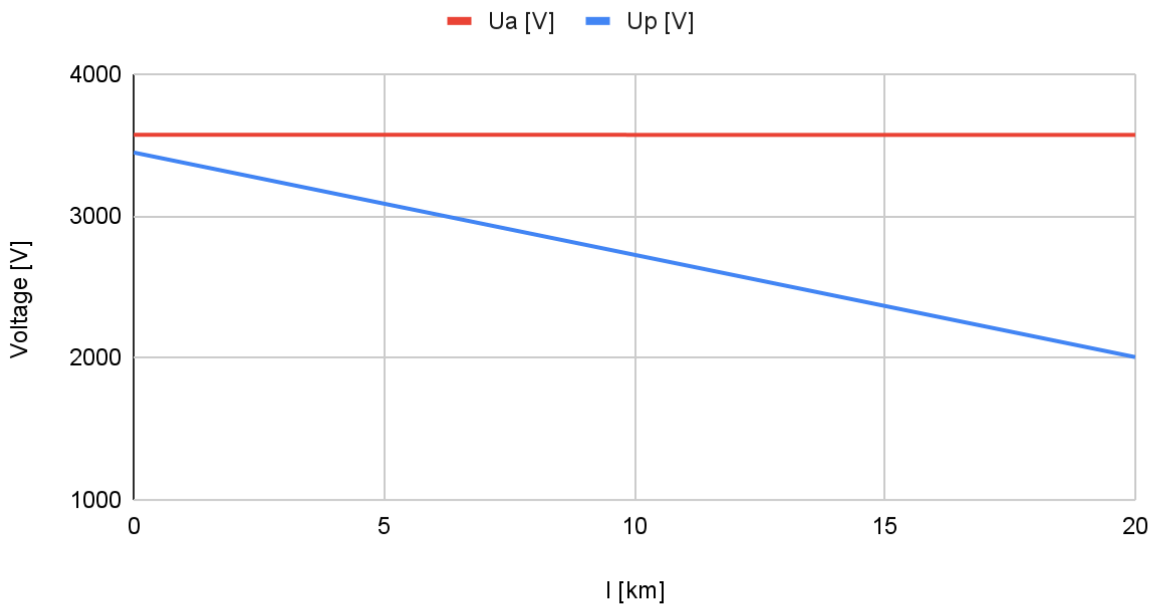

Figure 41. Graph of pantograph and output voltages of traction substation.

As shown in Figure 41, the output voltage of the substation Ua remains constant at 3497.53 V, which is approximately 74 V lower than the calculated no-load voltage of 3571.25 V derived from the substation simulation. This voltage discrepancy is attributable to voltage drops that occur under load conditions due to the resistance of the conductors and other components in the system. Specifically, the internal resistance of the rectifier units, denoted as 0.074 Ω, contributes to this voltage drop, resulting in the observed 74 V reduction.

On the other hand, the Up voltage, which is the voltage experienced at the pantograph (the point of contact between the train and the overhead line), starts at 3,446.15 V at l = 0 km. As the distance increases, Up significantly decreases, reaching 2,005.29 V at l = 20 km. This considerable drop in pantograph voltage indicates that as the train moves further away from the power supply, the voltage it receives diminishes. The reduction in voltage at the pantograph as the locomotive moves farther from the substation is primarily due to the electrical resistance, reactance, and impedance of the overhead line. These factors cause a cumulative voltage drop, leading to lower available voltage at the pantograph as distance from the power source increases.

Table 6. Results of simulations for two-sided power supply in case of traction current 1 kA.

l [km]	**0**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
Up [V]	3455.41	3344.92	3258.98	3197.59	3160.76	3148.49	3160.76	3197.59	3258.98	3344.92	3455.41
Ia [A]	926.02	840.82	755.61	670.41	585.2	500	414.8	329.59	244.39	159.18	73.98
Ib [A]	73.98	159.18	244.39	329.59	414.8	500	585.2	670.41	755.61	840.82	926.02
Va [V]	3502.99	3509.27	3515.55	3521.83	3528.11	3534.39	3540.68	3546.96	3553.24	3559.52	3565.8
Vb [V]	3565.8	3559.52	3553.24	3546.96	3540.68	3534.39	3528.11	3521.83	3515.55	3509.27	3502.99

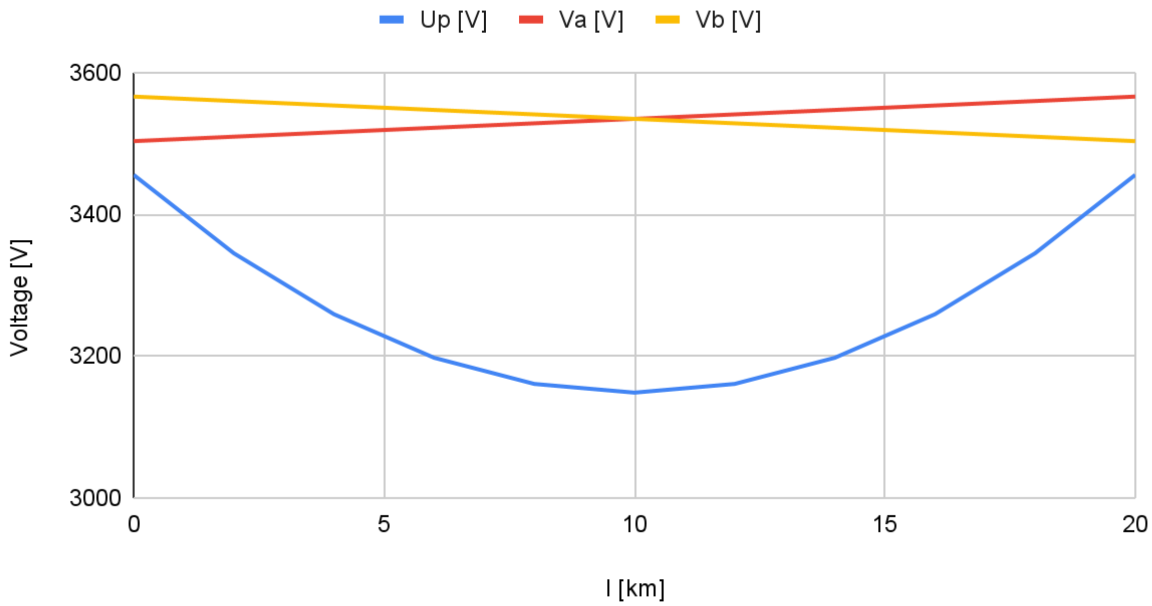

Figure 42. Graph of pantograph voltage of two-sided power supply system.

In the two-sided power supply system, the voltage Up at the pantograph starts at 3,455.41 V at both l = 0 km and l = 20 km. As the locomotive moves along the section, Up decreases slightly, reaching its lowest value of 3,148.49 V at l = 10 km, which is the midpoint of the section. This symmetrical voltage profile is characteristic of a two-sided supply system, where voltage tends to be lowest in the middle of the section and increases towards the supply points at either end as shown in Figure 42.

The voltage profiles Va and Vb exhibit distinct characteristics along the distance from the power source. The voltage Va increases steadily with distance, rising from 3502.99 V at l = 0 km to 3565.8 V at l = 20 km. In contrast, Vb displays a decreasing trend, starting at 3565.8 V at l = 0 km and dropping to 3502.99V at l = 20km.

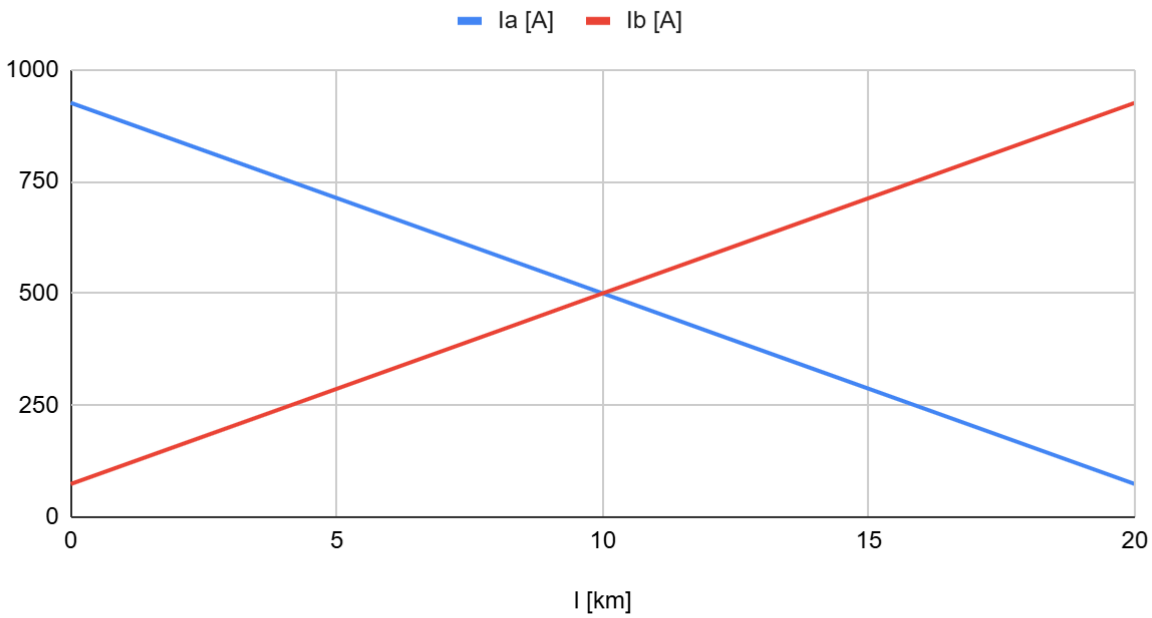

Figure 43. Graph of the current at the start and the end point of the sections.

The current Ia at the start of the section decreases as the distance from the start increases, starting at 926.02 A at l = 0 km and dropping to 73.98 A at l = 20 km. This trend, which is shown in Figure 43, reflects the fact that as the locomotive moves further from the start of the section, more of the current is supplied by the opposite end (the end of the section).

Conversely, the current Ib at the end of the section follows the opposite pattern. It starts low at l = 0 km (73.98 A) and increases to 926.02 A at l = 20 km. This increase shows that as the locomotive approaches the end of the section, more current is drawn from the power supply at that end. This behaviour, like Ia, reflects the balanced nature of the two-sided supply system, where both ends of the section contribute to the power supply depending on the locomotive's position.

Table 7. Calculation result of the two-sided with sectioning cabin simulation.

l [km]	**0**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
Up [V]	3471.67	3366.7	3299.45	3269.92	3278.1	3324	3278.1	3269.92	3299.45	3366.7	3471.67
Ia [A]	899.66	815.58	731.5	647.42	563.34	479.26	563.34	647.42	731.5	815.58	899.66
Ib [A]	100.34	184.42	268.5	352.58	436.66	520.74	436.66	352.58	268.5	184.42	100.34
Va [V]	3504.93	3511.13	3517.33	3523.53	3529.72	3535.92	3529.72	3523.53	3517.33	3511.13	3504.93
Vb [V]	3563.86	3557.66	3551.46	3545.26	3539.06	3532.87	3539.06	3545.26	3551.46	3557.66	3563.86

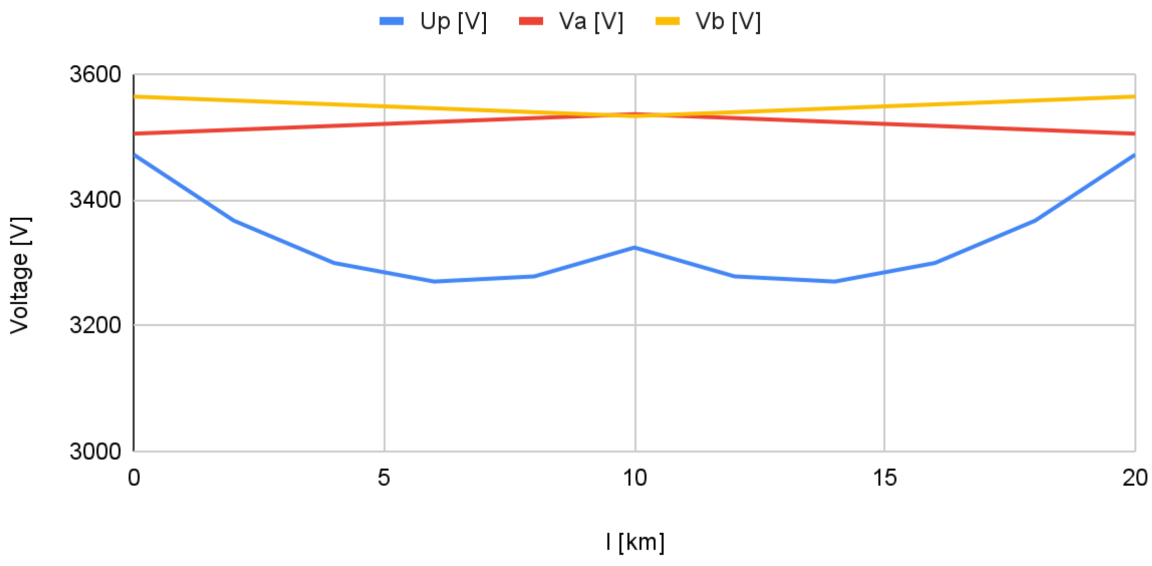

Figure 44. Examples of voltages of traction substations A and B, and pantograph voltage of the locomotive.

The pantograph voltage Up starts at 3,471.67 V at both ends of the section (l = 0 km and l = 20 km). As the locomotive moves towards the middle of the section, Up decreases, reaching its lowest value of 3,269.92 V at l = 6 km and l = 14 km, which are near the middle points of the section, with a slight increase around l = 10 km (3,324 V). This behavior, shown in Figure 44, suggests that the sectioning cabin plays a role in stabilizing the voltage around the midpoint, preventing a significant drop.

The voltage Va at the start of the section begins at 3,504.93 V and slightly increases as the locomotive moves towards the midpoint, reaching a maximum of 3,535.92 V at l = 10 km.

Similarly, Vb at the end of the section starts at 3,563.86 V and decreases slightly as it approaches the midpoint, with a minimum of 3,532.87 V at l = 10 km. The gradual change in Va and Vb across the section is due to the changing distribution of the load between the two supply points. In a two-sided power supply system, power is fed into the system from both ends of the section. As the locomotive draws power, the voltage at the points where power is injected into the system (Va at the start and Vb at the end) will generally be higher near the supply points and decrease with distance due to the impedance of the line.

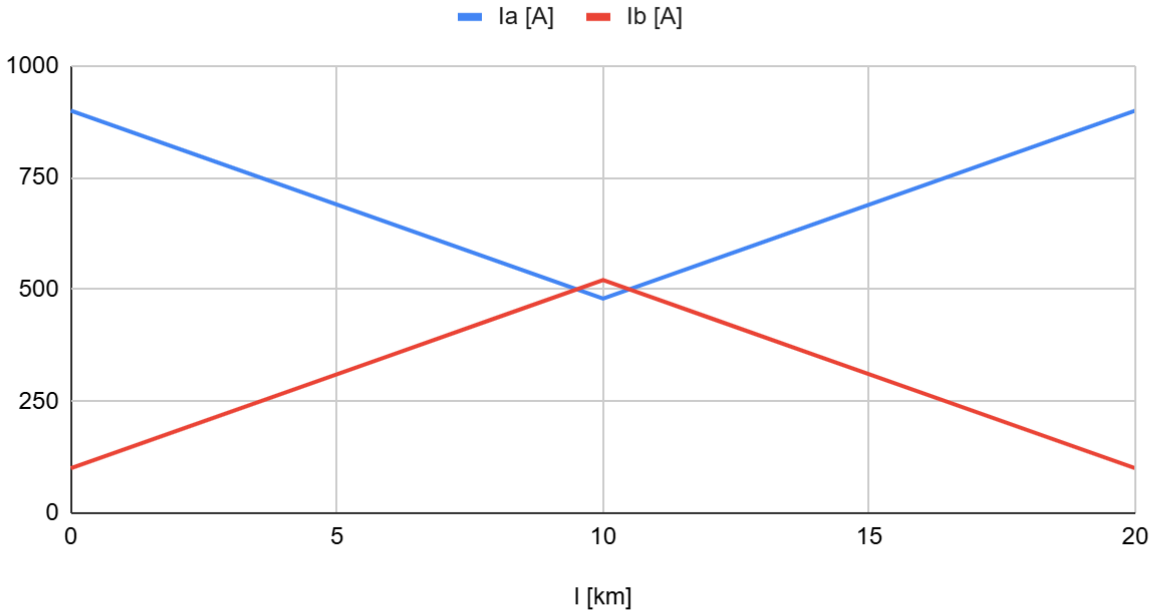

Figure 45. Examples of currents of tractions substations A and B localized at the start and the end point of the section.

The current Ia at the start of the section starts at 899.66 A and decreases towards the middle, reaching 479.26 A at l = 10 km before increasing again towards the end, where it mirrors the initial value (899.66 A at l = 20 km). Conversely, Ib starts at 100.34 A at l = 0 km and increases symmetrically towards the middle, reaching 520.74 A at l = 10 km before decreasing again as it approaches the end of the section. As depicted in Figure 45, It shows similar trends to a two-sided power supply system, showing that power is provided from both ends of the section, with the current drawn from each end depending on the locomotive's position along the track. The difference is that the sectioning cabin located near the middle of the section helps manage the distribution of current between the two supply points, preventing significant current drop. As the locomotive moves from one end toward the other, the sectioning cabin ensures that the load is shared more evenly between the two ends.

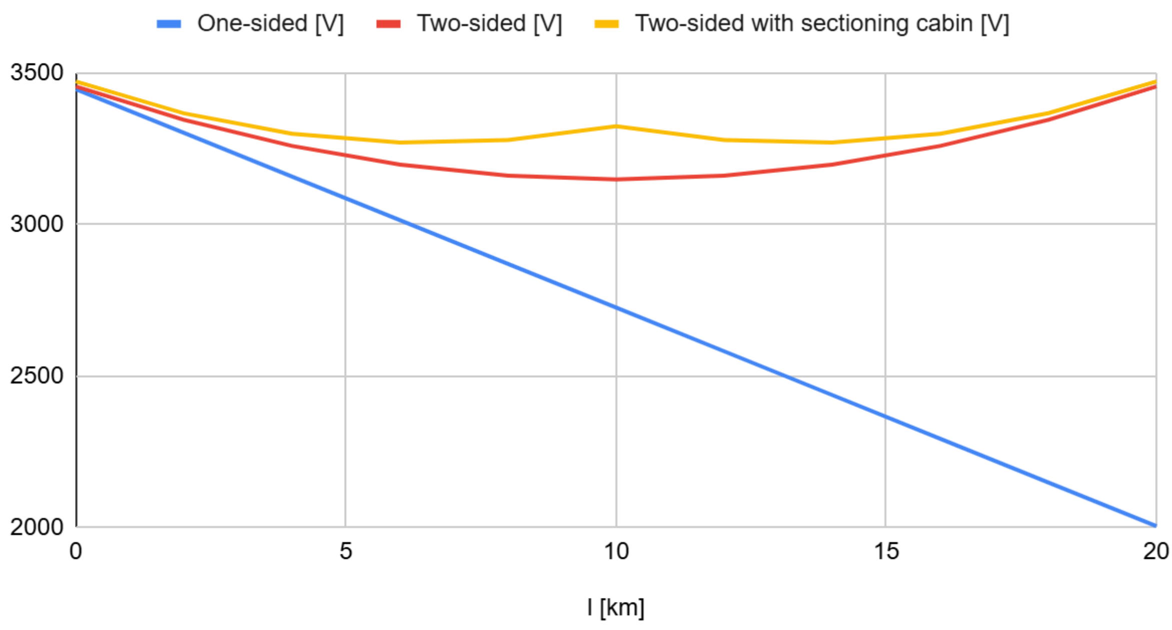

Figure 46. Graph of pantograph voltages of all three types of power supply systems.

Figure 46 shows the comparison of the Up (pantograph voltage) from the one-sided, two-sided, and two-sided with sectioning cabin power supply systems on a single graph, the distinct characteristics of each system become apparent, reflecting the differences in how power is supplied and distributed along the track.

In a one-sided supply system, the pantograph voltage Up shows a steady decrease as the distance from the substation increases. This characteristic is due to the fact that power is supplied from only one end of the track, and as the locomotive moves further away from the substation, the resistance in the line causes a significant voltage drop. This results in a continuous decline in Up, particularly over long distances, which can limit the system's ability to deliver consistent power to the locomotive.

The two-sided supply system exhibits a different voltage profile. Here, Up initially decreases as the locomotive moves away from one substation but then stabilizes as it approaches the midpoint of the section. As the locomotive continues toward the second substation, Up begins to rise again. This characteristic is due to the dual supply points at either end of the track, which help balance the voltage and minimize drops by sharing the load. The result is a more stable voltage profile across the entire section, with the lowest point occurring near the middle, reflecting the balanced contribution of both substations.

In the two-sided supply system with a sectioning cabin, the voltage profile is further refined. The graph shows a more stable Up throughout the section, with only slight variations. Near the midpoint, Up stabilizes, reflecting the role of the sectioning cabin in evenly distributing power from both supply points. The sectioning cabin helps manage the load more effectively, reducing voltage fluctuations and ensuring a more consistent voltage along the entire track. This system offers the most stable voltage profile of the three, which is crucial for maintaining efficient and reliable power delivery to the locomotive.

Overall, the combined characteristics in the graph illustrate how power supply configuration significantly impacts the voltage available to the pantograph. The one-sided system shows a clear disadvantage in maintaining consistent voltage over distance, while the two-sided systems, especially with a sectioning cabin, provide much more stable and reliable power distribution.

5.3. Demonstration of the short-circuits simulation

For the demonstration of short-circuit simulation, the same parameters are used as the traction system simulation except that the parameters of type of traction power supply and locomotive current are not used since they are not needed. The following is the procedure for the substation simulation:

1) Choose ‘Main railway 3 kV DC’ and ‘short-circuit’ in the first window.
2) For each section of the parameters (HV line, PCC Transformer, MV line, Rectifier unit) choose or input the desired parameters.
3) Ensure that you use a period instead of a comma for decimal points and review all the parameters to ensure they are correctly inputted.
4) Press the calculate button at the bottom of the window to proceed to the calculation results.
5) Note: Using a comma will trigger an error window that may cause the program to crash.

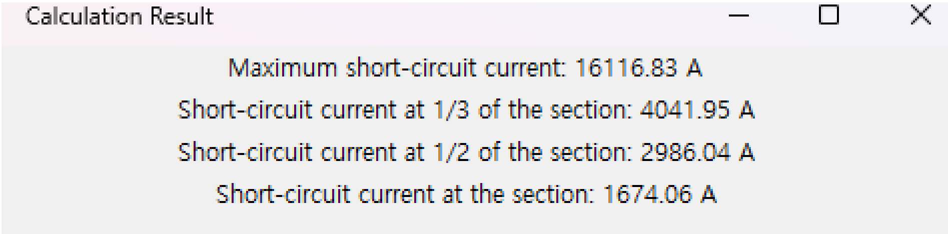

Figure 47. Calculation result window of the short-circuit simulation.

The result of the calculation of the short-circuit simulation is shown in Figure 47 and it is as follows.

- Maximum short-circuit current [A]: **16116.83**
- Short-circuit current at ⅓ of the section [A]: **4041.95**
- Short-circuit current at ½ of the section [A]: **2986.04**
- Short-circuit current at the section [A]: **1674.06**

The Maximum Short-Circuit Current, calculated to be 16,116.83 A, represents the highest current that would flow through the system during a short-circuit event. This is a critical parameter for the design and protection of the electrical network. Circuit breakers, protective relays, and other safety devices must be rated to handle and interrupt this high level of current to prevent damage to equipment and ensure the safety of the system.

The Short-Circuit Current at ⅓ of the Section, which is 4,041.95 A, shows how the short-circuit current diminishes as it progresses further along the line from the source of the fault. This value is important for understanding the current levels that protective devices closer to the fault might need to manage. It provides insight into the distribution of fault current along the line and helps in the placement and calibration of protective equipment.

Similarly, the Short-Circuit Current at ½ of the Section, calculated at 2,986.04 A, further illustrates the reduction in short-circuit current as the distance from the fault increases. This value is lower than the current at ⅓ of the section, indicating that the fault current continues to decrease as the impedance of the line increases with distance. This information is valuable for ensuring that protection settings are appropriate throughout the network, not just near the substation.

The Short-Circuit Current at the Section, measured at 1,674.06 A, represents the current at the farthest end of the section under a short-circuit condition. This value is significantly lower than the maximum short-circuits current, which is expected due to the increased impedance encountered as the distance from the fault increases.

6. Conclusions

As a result of the conducted research in this thesis, I have successfully developed a sophisticated virtual simulator for studying electrified railway systems, replacing traditional physical laboratory setups. This advanced tool, constructed using Python's extensive libraries, significantly enhances analytical capabilities for both students and researchers. By providing superior accuracy and precision in evaluating basic components of electrical transportation systems – such as substation voltage, traction systems, and short-circuit scenarios across railways – the simulator represents a major advancement in educational quality and research.

While the program may not capture every nuance of real-world scenarios in exhaustive detail, it offers a versatile and accessible platform for conducting essential analyses and simulations that would otherwise require more resource-intensive setups. Its key strength is its capacity to replicate important elements of railway electrification, offering a dependable framework for researchers and students to investigate the underlying concepts and operational issues of electrified railway systems. Although it may not account for every variable or severe scenario, the simulator's degree of analysis is critical for establishing a basic knowledge before moving on to more specialized or extensive investigations.

The program's straightforward design and reliance on Python's libraries make it highly accessible, even for those who may not have extensive experience with more complex simulation tools. This accessibility broadens the study of electrified railway systems, allowing a broader range of students and researchers to engage with the material and conduct meaningful experiments. In an educational context, this significantly enhances the learning experience by enabling hands-on interaction with key concepts and scenarios that would otherwise be difficult to replicate.

Furthermore, the simulator's influence goes beyond academic contexts. While it may lack the granularity required for very extensive study, it serves as a good foundation for more complete inquiries. Researchers can utilize the information gathered from this simulator to inspire more advanced investigations, such as improving simulations or designing real tests. In this sense, the software contributes to a layered approach to study, in which preliminary discoveries may be gradually expanded to attain greater depth and knowledge.

Based on my research and analysis of the results, I have concluded that the simulator enables more detailed and comprehensive analyses while minimizing human error. This achievement marks a substantial improvement in the quality of research and education in electrical transportation systems. While it may serve as a foundational tool rather than an exhaustive solution, its value lies in its accessibility, ease of use, and ability to model fundamental aspects of electrified railway systems effectively. The simulator stands as a crucial tool for both educational purposes and as a stepping stone toward more detailed research, ultimately contributing to the broader field of electrical transportation systems.

To my individual achievements in this thesis, I can include the following:

- improvement of the working skills in AutoCAD, MS Office;
- deepening knowledge about the electric traction and power supply theory;
- practice the creation of programs using Python.

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