

Article

Feasibility Study of Traction Power Supply for Medium-Capacity Rail System Based on Rigid Overhead Conductor Rail System: Case Study on Pham Van Dong Route in Ho Chi Minh City, Vietnam

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Abstract: In this article, we advance a model for the traction power supply of a medium-capacity railway system along the major Pham Van Dong (PVD) arterial route situated in the northeastern sector of Ho Chi Minh City (HCMC), Vietnam. This study simulates an in-depth analysis of the carrying capacity and feasibility of traction power supply for this scenario based on a safe moving-block system utilizing Communications-based Train Control (CBTC). The research results show that the 750 V DC traction system uses a rigid overhead conductor rail system (ROCS) with distances between traction power stations of up to 6 km with double feeding. The system provides a service frequency of 36 trains per hour per direction, and has a transport capacity of up to 47,520 passengers per hour per direction. The implementation of this solution, as proposed, has the potential to improve traffic flow, reduce congestion, reduce environmental pollution, and provide a complete and modern urban railway network for HCMC. The system could also be implemented in other similar global scenarios. Additionally, this investigation also demonstrates the feasibility of applying the new ROCS to medium-capacity railway systems (MCSs), which have garnered increasing attention in recent years owing to their discernible advantages over extant systems. The outcomes of this study underscore the pragmatic nature of the proposed solution, which orients sustainable and integrated development in the realm of urban rail transport.

Keywords: traction power supply; medium-capacity rail system; DC third rail; rigid overhead conductor rail; integrated urban railway



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1. Introduction

In recent years, MCSs have been introduced with outstanding advantages. They can meet the traffic capacity range that bus rapid transit (BRT) (from 5400 passengers per hour per direction (p/h/d) to 10,800 p/h/d) and light rail transit (LRT) (from 18,000 p/h/d to 24,000 p/h/d) provide, but cannot meet the requirements of mass rapid transit (MRT) (from 18,000 p/h/d and up), with construction costs being too expensive [1–4]. The definition of an MCS varies due to their non-standard nature. MCSs have a capability of boarding around 20,000–30,000 passengers per hour per direction (p/h/d), and can even board up to 48,000 p/h/d [5–11]. Therefore, after an in-depth survey and analysis of the traffic flow of 29,595 motorcycles during peak hours in the direction of the Pham Van Dong (PVD) route, we proposed an average railway system model to guide and solve the traffic problems on the main road of PVD in the northeast of Ho Chi Minh City (HCMC), Vietnam, submitted in an article with the title “Research on Medium Capacity Rail System: Case on Pham Van Dong Route in Ho Chi Minh City, Vietnam” [11]. In this article, we continue to study

the feasibility of a traction power supply system for system operations with the largest carrying capacity.

In traction power supply, there are important issues that are of concern, including power supply, traction power, useful voltage at the pantograph, contact line systems, and supply schemes [12–17]. Power supply, including a bulk supply substation and an internal power distribution system, must comply with national or regional voltage standards, and must be synchronized with the existing urban railway planning system. The traction power demand estimation must ensure reliability and flexibility in cases of normal operation, overload, fault, and the development of the prevention of load [18,19].

In addition, the contact voltage must be suitable for the type of load, ensuring that the voltage can operate during peak hours with the largest service frequency, as well as at low voltage, according to the reliable standard EN 50468 [20]. The voltage in contact line networks has a great influence on the carrying line capacity [21]. The contact line system is required to ensure that the important factors of good electrical conductivity and low voltage drop. There are also other related issues, such as beauty, total installation and operation costs, and operating speed [22].

Finally, the supply scheme plays another important role in distributing the exit current that directly affects the reliability of supply and the quality of contact voltage when operating. Therefore, it is very important that the design of traction power supply for new systems carefully considers the above issues. At the same time, applying new technology is necessary to avoid obsolescence and wasting capacity, and to improve system reliability and quality [22–24].

In this study, we will calculate the capacity required for the system to operate in both normal and incident cases. At the same time, we will conduct an in-depth analysis of the power supply options, as well as the traction current distribution structure of the 750 V DC traction system with a third rail system, overhead catenary system (OCS) [25–28], and ROCS [22,29–38]. In particular, the choice of ROCS in this research is one that we hope will become common in the near future because of its outstanding advantages. Furthermore, this will be a transparent scientific basis for choosing an effective power supply structure for the synchronous and sustainable development of urban railway transport networks [39–43].

The rest of this paper starts with an explanation of the synchronization and reliability provided by the power supply system design. Then, the traction power distribution system is presented in Section 2. Section 3 outlines the system design and the design method for traction load. The results and discussion are presented in Section 4. Finally, Section 5 provides a brief conclusion and considers future research work as well.

2. Synchronization and Reliability Provided by Power Supply System Design

2.1. Sources of Power Supply

To ensure reliability, similar to the subway system, the MCS is supplied with power with voltage levels of 22 kV from the bulk supply substation (BSS), receiving two high-grid-voltage sources of 110 kV and 220 kV [12–14] in alternating current (AC) at a frequency of 50 HZ, synchronized with the existing Line 1 and Line 2 of the HCMC Metro. The 22 kV of power will be distributed along the alignment through the main cable ring network for feeding traction and auxiliary loads. Keeping in view the reliability requirements, two bulk supply substations (BSSs) are proposed to be set up for the line [24–28]. The plan includes one BSS located near the Binh Trieu maintenance depot in Phase 1, and the remaining BSS located near the end station of the PVD line at Gia Dinh Park in Phase 2. In Phase 1, the route will be 8.07 km long from the Linh Xuan intersection to Binh Trieu station, including a BSS with five traction substations along the road and one at the depot. The 22 kV internal power distribution system (PDS) will be distributed along the alignment through the 22 kV ring main cable network for feeding traction and auxiliary loads [44].

Train operation requires converting 22 kV power to 750 V DC at the traction substations, which then supply the power lines along the railway tracks. In addition, the 22 kV AC power is simultaneously reduced to 400 V AC in three phases and supplied to the

equipment for communication, signaling, and other uses by an uninterruptible power supply. Two substations supply enough electricity to power the entire system, and either substation can do so [14,44].

2.2. Traction Power Substation

Because of its high-frequency service, the MCS electrical load has unique power consumption characteristics and is regarded as a first-class priority electrical load. Therefore, stricter regulations are needed to deliver power to the subway. The traction power supply system for the MCS generally has the following technical features [12–19,21–28]:

The DC system traction power substation (TPS) consists of AC/DC converters including a rectifier transformer (RTT) and uncontrolled rectifier (SR). Transformer-rectifier groups (TSR) are in line with EN 50328, EN60146-1-1, NEMA RI9, and IEC 62590 connection schemes [12–19,21–28,45–49], for example, star, delta/delta, star—three-phase bridge; delta, star/star, delta—parallel bridge or series bridge; delta, star/double star—six-phase half wave with an interphase transformer (reactor); etc.

The number of group rectifiers will depend on the type of capacity traction substation, since there can be 2 or 3 groups of rectifiers, and normally they will include a spare set for emergency situations. The transformer-rectifier groups are duty class VI according to the above standards.

A traction power substation includes a 22 KV ac insulated power cable and accessories, 750 V DC switchgear, negative panels, a traction power feeding substation (TPFS), a traction return bond, low-voltage AC switchgear assemblies, auxiliary step-down transformers (AC system), 110 V batteries and chargers for control power supply, a local annunciator panel and 110 V DC distribution panel boards, supervisory control and data acquisition (SCADA) interface provisions (including Interfacing Panel), a low-voltage AC insulated power cable and accessories, a 750 V DC insulated power cable and accessories, outgoing DC disconnect switches as may be required for isolation purposes, control cables and accessories, installation materials, an earthing system, bonding, corrosion control, ventilation, and regenerative energy storage systems [13–17,24,26–28,50].

Every piece of electrical equipment is linked to the operation control center's specialized SCADA system, which controls the power supply by turning it on and off and keeping an eye on the equipment's charged state and status.

2.3. Traction Power Distribution System

2.3.1. Contact Line System

In the urban railway system, for the 750 V DC voltage level, the third rail is commonly used for subway systems, while the OCS is preferred for the LRT systems because of their advantages and disadvantages [13,14,25–28]. However, the recent emergence of ROCS requires further study for its application in this context.

There are three options available for the power supply system for MCS at PVD, with the following main advantages and disadvantages (technical):

Flexible OCS: One of the outstanding advantages is connecting the current collector devices continuously during level crossings and at crossovers. However, drawbacks include large voltage drops, contact wire sags, tensioning equipment, and complex catenary wires.

Third rail system (3R): The primary advantage is its ability to withstand large load traction currents and a low voltage drop. However, a major safety concern is the interruption of current collection at level crossings and crossovers, posing a higher risk to human life compared to OCS.

Rigid overhead conductor rail system (ROCS): This system comprises a treated aluminum body, in a clamp shape that holds the copper contact wire in place, providing greater stiffness and a greater circuit section that allows for the removal of parallel conductor cables at voltages ranging from 750 to 1500 V and can accommodate voltages up to 25 kV [22]. The ROCS comprises different elements described in the following figures, Figures 1 and 2, and the conductor rail profile in Table 1:

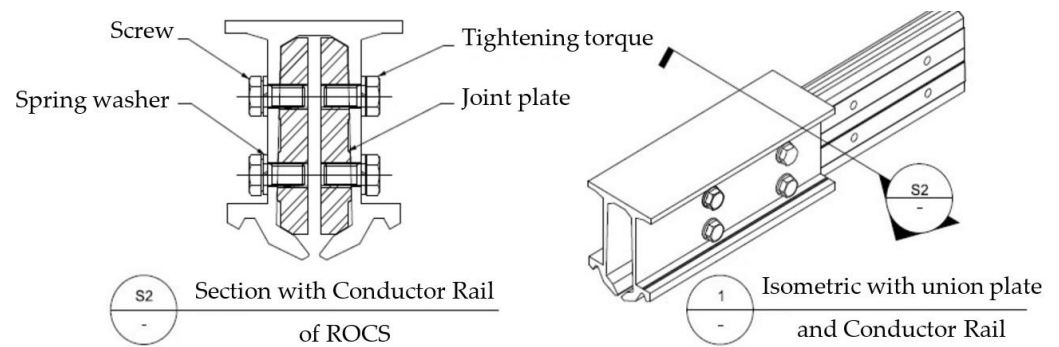


Figure 1. Conductor rail of ROCS.

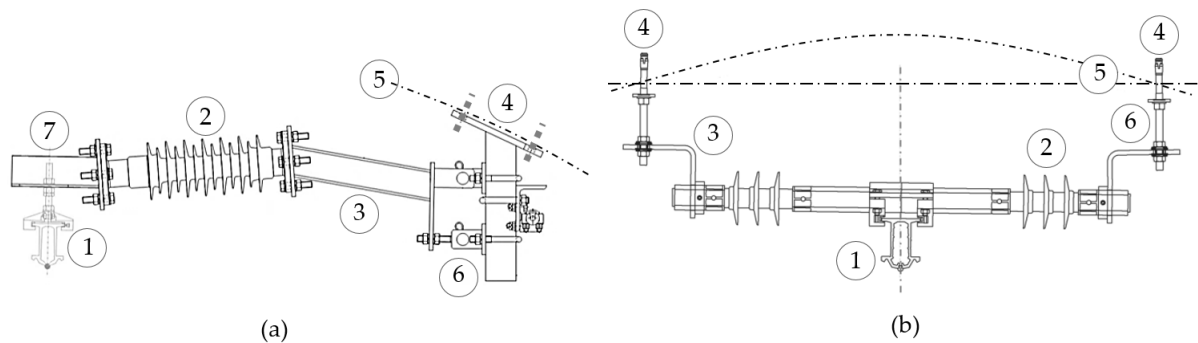


Figure 2. Types of ROCS installation: (a). Cantilever; (b). Crossbar support, in which there are (1). Conductor rail; (2). Insulator; (3). Rear bracket/suspension structure; (4). Anchor bolt; (5). Bracket cantilever/suspension/tunnel ceiling; (6). Fixed or sliding hanger clamp; (7) Standoff.

Table 1. Characteristics of the aluminum profile.

Parameters	Height	
	110 (mm)	80 (mm)
Profile Section (mm ²)	2220	2202
Moment of Inertia I _{xx} (mm ⁴)	338×10^4	164.26×10^4
Moment of Inertia I _{yy} (mm ⁴)	113.7×10^4	106.53×10^4
Weight (kg/m)	6.10	5.95
Equivalent Copper Section (mm ²)	1400	1234
Coefficient of Linear Expansion	24×10^{-6}	24×10^{-6}
Young's Modulus (N/mm ²)	69,000	70,000

The conductor rail of ROCS is manufactured by extrusion in aluminum alloy 6106 T5, thermally treated, according to EN 573-3:2009 [51] standards, in lengths of 10 m or 12 m or lower depending on the assembly conditions. It can be manufactured with two heights, normally 110 mm and 80 mm or similar, depending on the existing gauges, and cross-sections are 2202 mm² and 2223 mm². The structure includes the following components: a conductor rail, conductor inter-locking joints, a union plate, support and clamps, movable arms, a transition element, an electrical connection clamp, anti-creep clamps, earth clamps, a protection cover, a joint and end cap, a cable connection source, and an insulator [22,29–38]. The ROCS converges on all the outstanding advantages of OCS and 3R, eliminating the limitations of both OCS and 3R [22]. It can be used interchangeably with the two types, OCS and 3R, because of the following advantages:

- (a) Allows smaller tunnel cross-sections for new constructions;
- (b) Allowing lower support columns;
- (c) Allows a replacement electrification of tunnels and stations originally built for the third rail system;
- (d) Offers highly electrical cross-sections, so that additional feeders can be avoided;
- (e) Fire resistance is significantly greater than that of a catenary system;
- (f) Extreme operational reliability and requires little maintenance regardless of the operating voltage;
- (g) Faster installation.

2.3.2. Distribution Traction System

Single-end feed: In this system, the trains draw current from one direction by a TPS [13,14,21,52–65]. The advantages of this network include its simplicity, ease of installing security devices, and uncomplicated operation. However, a disadvantage is that it experiences a significant voltage drop along the line, which reduces the passenger carry capacity.

Double-end feed: In this system, trains draw current from the two directions by two adjacent TPSs [21,52–65]. The benefits include a reduced voltage drop in the contact line, extended supply distance, and higher transport capacity. However, this network has a more intricate structure, necessitates the installation of intricate protection devices, and requires difficult maintenance.

3. System Design

3.1. Design Method Traction Load

In the traction power design, one TPS's power source must be able to meet the power requirements of every train within its scope of supply. The operating plan must meet the greatest traffic demand in each cycle.

Annotate the components in Formulas (1) to (36), and the parameters necessary for simulation calculations are defined in Table 2.

Table 2. Variable definition.

Variable	Definition	Value/Unit
V_f	maximum traffic flow value	motorcycle/hours/direct
A_f	traffic actual flow	motorcycle/hours/direct (m/h/d)
PHF	peak hour factor	-
5P	passenger volume during the peak 5 min	person
j	the times	-
n	integer	-
D_{e-max}	maximum traffic demand in each period	-
PDF	traffic growth coefficient	-
k_c	demand coefficient	-
C_{L-max}	person capacity	person/hour/direct (p/h/d)
T_{c-max}	line capacity	train/hour/direct (t/h/d)

Table 2. Cont.

Variable	Definition	Value/Unit
$C_{t-\max}$	maximum person per train on schedule	person/train
n_c	number of the car	cars
L_c	car interior length	meters
$L_{t-\max}$	longest train length	meters
L_{st}	longest station length	meters
p_t	person per meter of train length	persons/meter length
$H_{s-\min}$	station headway	seconds
d_{eb}	distance from the front of the stopped train to the start of the station exit block	meter
v_a	station approach speed	meters/second
$v_{\max}$	maximum line speed	meters/second
k_{br}	braking safety factor	worst-case service braking is $k_{br}\%$ of the specified normal rate
B	separation safety factor	2.4 three-aspect, 1.2 cab signal, and 1.0 moving block
t_{os}	time for overspeed governor to operate	seconds
t_{jl}	time lost to braking jerk limitation	seconds
t_{br}	brake system reaction time	seconds
t_d	dwel time	seconds
t_{om}	operating margin	seconds
a_s	initial service acceleration rate	m/s^2
d_s	service deceleration rate	m/s^2
a_g	acceleration due to gravity	m/s^2
G_i	grade into station	%
G_o	grade outstation	%
l_v	line voltage as a percentage of specification	90%
P_e	positioning error—moving block	meter
S_{mb}	block safety distance—moving block	meter
a	train acceleration	m/s^2
g	constant of gravity	m/s^2
ζ	specific allowance for rotating masses	
R_g	train gradient resistance	‰
R_{cv}	train resistance due to curves	‰
A, B, C	Davis equation coefficient in the train rolling resistance	

Table 2. Cont.

Variable	Definition	Value/Unit
P_t	maximum instantaneous power according to tractive effort	kilowatt
P_{aux}	auxiliaries' power	kilowatt
η_c, η_m	machine efficiency, motor efficiency	%
$p_{tps(i)-n}^{pre}$	power calculated under normal conditions without regenerative braking	kilowatt
$p_{tps(i)-n}^{pre}$	power calculated under normal conditions with regenerative braking	kilowatt
$p_{tps(i)-er}^{pre}$	power calculated under fault conditions without regenerative braking	kilowatt
$p_{tps(i)-er}^{pre}$	power calculated under fault conditions with regenerative braking	kilowatt
U_{d0}	rectifier voltage	voltage
U_d	voltage at rated traction current at TPFS	voltage
I_{tr}	rated traction current	ampere
$n_{t(tpsi)}^{cse}$	train number per segment in each case	
v_{sc}	operating schedule speed	kilometers per hour
R_o	total source resistance	ohm
ΔU_x	voltage drop at x	volt
D_{tps}	length section between two adjacent TPSs	km
R_{trac}	loop resistance of the contact line system	ohm per kilometer
j	train numbers from 1 to m_t	
x	at position x	kilometer
L	power supply segment	kilometer
D	distance between two TPSs	kilometer

According to [11], based on the calculation results for the operating plan with the smallest allowable distance, corresponding to the largest number of trains to serve, from here, we choose to operate the route with a train control signal system with moving-block variable safety distance; results in minimum headways of H_s seconds are summarized as follows:

$$PHF = \frac{1}{n} \times \sum_{j=1}^n \frac{A_{fj}}{12 \times 5P} \quad (1)$$

$$V_f = A_{fmax} \times PHF \quad (2)$$

$$D_{e-max} = V_f \times PDF \times k_c \quad (3)$$

$$C_{t-max} = L_{t-max} \times p_t \quad (4)$$

$$\text{With conditions : } \begin{cases} L_{t-\max} = n_c \times L_c \\ L_{t-\max} \leq L_{st} \\ 4 < p_t \leq 13.5 \end{cases} \quad (5)$$

$$H_{s-\min} = \frac{L_t + P_e}{v_a} + \left(\frac{100}{k_{br}} + B \right) \times \left(\frac{v_a}{2 \times d_s \times (1 + 0.1 \times G_i)} \right) + \left(\frac{a_s \times (1 + 0.1 \times G_i) \times t_{os}^2}{2 \cdot a_s} \right) \cdot \left(1 - \frac{v_a}{v_{\max}} \right) + t_{os} + \sum t \quad (6)$$

$$\sum t = t_{jl} + t_{br} + t_d + t_{om} \quad (7)$$

$$T_{s-\max} = \frac{3600}{H_{s-\min}} \quad (8)$$

$$C_{L-\max} = T_{s-\max} \times C_{t-\max} \quad (9)$$

With the following conditions:

$$C_{L-\max} \geq D_{e-\max} \quad (10)$$

These should be rounded up to an integral number of trains per hour, that is, $H'_{s(\min)}$ seconds— $T'_{s-\max}$ trains per hour. From here, we can deduce the largest number of passengers transported in a train [11].

To solve the power consumption of train sets along the line by performing the train performance simulation, the running schedule and speed profile of train operation between two adjacent TPSs are used to define the acceleration, coasting, deceleration, and dwelling for each trip time of train operation. In the dynamics of a train's motion, the electrical power consumption has an inverse connection with mechanical and engine efficiency and a direct relationship with the speed of motion and the traction force needed to achieve it. If all additional resistances caused by the geography of the railway are ignored, the instantaneous maximum power required to move the train over one period of motion is as follows [53–61]:

$$P_{tR} = \frac{[(M_t + C'_{t-\max} \times m_p) \times g \times V]}{\eta_c \times \eta_m \times 3.6} \times \left[\left(\frac{a}{g} \times \xi \times 10^3 \right) + (A + B \times V + C \times V^2) + R_g + R_{cv} \right] \quad (11)$$

$$P_t = P_{tR} + P_{aux} \quad (12)$$

Thus, the maximum instantaneous power of each i^{th} traction power station is determined for the following cases [44,57–61]:

$$P_{tps(i)-n}^{nre} = \frac{3600}{H'_s} \times \frac{2}{v_{sc}} \times D_{tps(i)} \times P_t \quad (13)$$

$$P_{tps(i)-n}^{re} = \frac{3600}{H'_s} \times \frac{2}{v_{sc}} \times D_{tps(i)} \times (1 - \eta_{re}) \times P_t \quad (14)$$

$$P_{tps(i)-er}^{nre} = \frac{3600}{H'_s} \times \frac{2}{v_{sc}} \times \left(D_{tps(i)} + \frac{D_{tps(i+1)}}{2} \right) \times P_t \quad (15)$$

$$P_{tps(i)-er}^{re} = \frac{3600}{H'_s} \times \frac{2}{v_{sc}} \times \left(D_{tps(i)} + \frac{D_{tps(i+1)}}{2} \right) \times (1 - \eta_{re}) \times P_t \quad (16)$$

The power of the substations depends on the effective peak values of the currents to be supplied; the power installed in the transmission substations must be sufficient to meet the expected load curve in the most severe operating classes and load limits following the NEMA RI9 [66] and IEC 60146-1-1 standards [67] (100% continuously, 150% for 2 h, 300% for 1 min, and 450% for 10 s). The TSR substations must be specified to meet a certain overload capacity, since the load curves are characterized by the large occurrence of power peaks of a short duration in the function of the possibilities of a simultaneous departure of

trains. Therefore, it needs to be determined through the condition of minimum values for mean useful voltage at the pantograph or maximum voltage drop [14,22,45].

The system is described as the TPS supply for double tracks, and the left and right sides of the TPS provide two directions, up and down, per track, so the voltage at the feeding station with total rated traction current is as follows [53–61]:

$$U_d = U_{d0} - I_{tr} \times n_{t(tpsi)}^{cse} \times \sum R_0 \quad (17)$$

In which I_{tr} is rate current traction per train, $n_{t(tpsi)}^{cse}$ is total trains in each feed section considering each case of normal operation and fault operation, and R_0 is total resistance from the traction substation to the Z switch of TPFS.

In the case of a single-end feeding power supply, the voltage drops from the TPS up to position x with several trains in the feed section, which can be written off as follows [52,53]:

$$\Delta U_x = R_{trac} \times \sum_{j=1}^{m_t} I_{tr,j} \times x_j \quad (18)$$

$$\Delta U_{\max:x_{mt} \rightarrow L} = R_{trac} \times \left[\sum_{j=1}^{m_t-1} I_{tr,j} \times x_j + I_{tr,mt} \times L \right] \quad (19)$$

In Formula (19), the maximum voltage drop $\Delta U_{\max:x_{mt} \rightarrow L}$ will occur when the m_t train reaches the far end of the section.

Now, consider the same case with uniformly distributed loads on L . The uniformly distributed current on the line for a large number of trains is given by the following [52,53]:

$$\Delta U_{x, \text{cond}: x < L} = \frac{1}{L} \times R_{trac} \sum_{j=1}^{m_t} I_{tr,j} \times \int_0^x (L - x) dx \quad (20)$$

$$\Delta U_{x, \text{cond}: x < L} = \frac{1}{L} \times R_{trac} \times \sum_{j=1}^{m_t} I_{tr,j} \times \left(L \times x - \frac{x^2}{2} \right) \quad (21)$$

For the hypothetical case where all trains are drawing equal currents I_{tr} at the peak hour, and where all trains travel along the section at a constant speed, from Formula (21) rewritten as Formula (22), the maximum voltage drop ($\Delta U_{\max}$) is as follows [52,53,59–65]:

$$\Delta U_{\max:x \rightarrow L} = \frac{1}{L} \times R_{trac} \times m_t \times I_{tr} \times \left(L \times x - \frac{x^2}{2} \right) \quad (22)$$

where R_{trac} is loop resistance per unit length (Ω/km), m_t is a train in a feed section, and x is distance from the feed; in Formula (22), there is a maximum voltage drop when a train is present at the end feed section ($x = L$).

In the case of a double-end feeding power supply, the length of the feed section is defined as $L_D = 2 \times L$. Assume that $U_{d(i)} = U_{d(i+1)} = U_d$ and that $R_{0(i, i+1)}$ is constant between all TPSs.

Assuming that there is one train moving between two traction substations at position x , the total traction current supplied from two adjacent TPSs, (i) and $(i + 1)$, is as follows [48,52,53]:

$$I_{tr(x)} = I_{t(i)} + I_{t(i+1)} \quad (23)$$

The voltage drop of the train at position x is

$$\Delta U_{x(i)} = x \times R_{trac} \times I_{t(i)} \quad (24)$$

$$\Delta U_{x(i+1)} = (L_D - x) \times R_{trac} \times I_{t(i+1)} \quad (25)$$

From Formulas (23) to (25), the result is

$$I_{t(i)} = I_{tr} \times \left(1 - \frac{x}{L_D} \right) \quad (26)$$

$$I_{t(i+1)} = I_{tr} \times \left(\frac{x}{L_D} \right) \quad (27)$$

From Formulas (26) to (27), they are rewritten for several trains [48,52,53]:

$$I_{t(i)} = I_{tr(1)} \times \left(1 - \frac{x_1}{L_D} \right) + \dots + I_{tr(mt)} \times \left(1 - \frac{x_{mt}}{L_D} \right) = \sum_{j=1}^{m_t} I_{trj} \times \left(1 - \frac{x_j}{L_D} \right) \quad (28)$$

$$I_{t(i+1)} = I_{tr(1)} \times \left(\frac{x_1}{L_D} \right) + \dots + I_{tr(mt)} \times \left(\frac{x_{mt}}{L_D} \right) = \sum_{j=1}^{m_t} I_{trj} \times \left(\frac{x_j}{L_D} \right) \quad (29)$$

If it is assumed that TPS(i) is a reference point, the voltage drop between two adjacent TPSs, (i) and (i + 1), calculated for a train at point x is as follows [48,52,53]:

$$\Delta U_{(i)x} = x \times R_{trac} \times \left(I_{t(i)} + I_{t(i+1)} \right) \times \left(1 - \frac{x}{L_D} \right) \quad (30)$$

In Formula (30), the maximum will occur at the point $x = L_D/2$.

Assuming that three trains are moving between two TPSs, (i) and (i + 1), there are voltage drops at position x_2 , and by substituting Formulas (28) and (29) into Formula (30) [48,52,53], the formulae are obtained as the following:

$$\Delta U_{(i)2} = R_{trac} \times \left[\frac{I_{tr1} \times x_1}{L_D} \times (L_D - x_2) + \frac{I_{tr2} \times x_2}{L_D} \times (L_D - x_2) + \frac{I_{tr3} \times x_2}{L_D} \times (L_D - x_3) \right] \quad (31)$$

From Formula (31), rewrite the kth train at point x:

$$\Delta U_{(i)x} = \frac{R_{trac}}{L_D} \times \left[\left(L_D - x_{(i)k} \right) \times \sum_{j=1}^k I_{trj} \times x_{(i)j} + x_{(i)j} \times \sum_{j=k+1}^{m_t} I_{trj} \times \left(L_D - x_{(i)j} \right) \right] \quad (32)$$

Similar to the case in Formulas (21) and (22), the following is the voltage drop at position $x < L_D/2$ [48,52,53]:

$$\Delta U_{x, \text{cond}: x < \frac{L_D}{2}} = \frac{R_{trac}}{L_D} \times \sum_{j=1}^{m_t} I_{trj} \times \int_0^x \left(\frac{L_D}{2} - x \right) dx, \quad (33)$$

$$\Delta U_{x, \text{cond}: x < \frac{L_D}{2}} = \frac{R_{trac}}{L_D} \times \sum_{j=1}^{m_t} I_{trj} \times \left(x \times \frac{L_D}{2} - \frac{x^2}{2} \right) \quad (34)$$

For the hypothetical case where all trains consume the same value of current, the maximum value of the voltage drop $\Delta U_{\max}$ occurs when $x = L_D/2$; Formula (34) becomes the following [48,52,53]:

$$\Delta U_{\max: x \rightarrow \frac{L_D}{2}} = \frac{1}{L_D} \times R_{trac} \times m_t \times I_{tr} \times \left(x \times \frac{L_D}{2} - \frac{x^2}{2} \right) \quad (35)$$

The minimum voltage in the contact line of the train drawing current at the end section for each operating condition is rewritten as follows [48,52,53,59–65]:

$$U_{tr-\min}^f = U_{d.0} - I_{tr} \times n_{t(tpsi)}^{cse} \times \sum R_0 - \Delta U_{\max}^f \quad (36)$$

The minimum values for mean useful voltage at the pantograph under normal operating conditions $U_{tr-\min}^f = U_{mu}$ must meet EN 50163 [68], UIC 600 [69], and IEC 60850 standards [70].

Finally, each traction substation's rated power must meet the requirements of NEMA RI9, EN 50328, and IEC 60146-1-1, and the lowest feeder voltage must meet the requirements of EN 50163, UIC 600, and IEC 60850; the characterization of the traction power supply fixed installations is according to the EN 50388 standard [71].

3.2. Design Parameter

According to [11], the demand coefficient for calculating traffic capacity for HCMC is 1.0, and the load parameters are in Table 3. The simulation calculation method using MATLAB R2017b (version 9.3) and results for the operating plan are summarized in Table 4. Then, the parameters for traction source design are listed in Tables 5–7 and the design results are in Tables 8 and 9.

Table 3. Data values for simulations.

Term Value	
Train length	120–200 m
A_f	29,595 m/h/d
PDF	100%; 150%; 200%
k_c	0.9–1.1
Front of train distance	10 m
k_{br}	75%
B	2.4; 1.2; 1.0
Overspeed governor time	3 s
Jerk limitation time	0.5 s
Controlling dwell time	30–45 s
Operating margin time	15–20 s
Service acceleration rate	1.3 m/s ²
d_s	1.3 m/s ²
P_e	6.25 m
Moving-block safety distance	50 m
G_i	1.5%
v_{max}	27.8 m/s
a_g	9.818 m/s ²

Table 4. Summary of the results of the operational plan simulation.

Parameters	Value
PHF	0.8
$D_{e-max-1}$ (Phase 1, 100%)	23,676 (p/h/d)
$D_{e-max-2}$ (Phase 2, 150%)	35,514 (p/h/d)
$D_{e-max-3}$ (Phase 3, 200%)	47,352 (p/h/d)
T_{s-min} (i)	60.2466 s
T_{s-min} (ii)	48.3310 s
T_{s-min} (iii)	35.0641 s
T_{s-min} (iv)	30.2846 s
H_{s-min} (i)	126.3713 s
H_{s-min} (ii)	113.3310 s
H_{s-min} (iii)	100.0641 s
H_{s-min} (iv)	93.7184 s

Table 4. Cont.

Parameters	Value		
T_{c-max} (i)	28.4875 (t/h/d)		
T_{c-max} (ii)	31.7654 (t/h/d)		
T_{c-max} (iii)	35.9769 (t/h/d)		
T_{c-max} (iv)	38.4129 (t/h/d)		
C_{L-max}	Phase 1	Phase 2	Phase 3
	(p/h/d)	(p/h/d)	(p/h/d)
C_{L-max} (i)	19,941	29,378	37,034
C_{L-max} (ii)	22,236	32,758	41,295
C_{L-max} (iii)	25,184	37,101	46,770
C_{L-max} (iv)	26,889	39,613	49,937

Note: Three-aspect fixed block (i), cab signal (ii), MVB fixed stopping distance (iii), and moving-block variable safety distance (iv).

Table 5. Operational plan and train traction load parameters.

Component	Unit	Value
Headway	[s]	100
Car length	[m]	31.72
Train length	[m]	126.88
Width	[m]	2.5
Seated/standing capacity	[p]	74/276
Person per square capacity (max)	[p/m ²]	7
Doors per side		5
Weight (driving cars), empty	[ton]	46.3
Weight (intermediate cars), empty	[ton]	46.0
Cars per train set		4
UIC		Bo'+2+2+Bo'
Axle load	[ton]	9.4
Acceleration/deceleration	[m/s ²]	1.0/1.3
Maximum speed	[km/h]	95
Maximum speed of schedule	[km/h]	57.6
Power output	[kw]	480
Auxiliaries + air conditioning rating	[w/person]	132
Electric traction system	[V DC]	750
Train rolling resistance		$1.5 + 0.03 \times V + 0.0002 \times V^2$

Table 6. Traction system design.

Option	Single-End Feed	Double-End Feed	Description
L_{PVD} [km]	8.07	8.07	Line length PVD
L_{TPS} [km]	1	1	Length section feeding of a TPS (or L)
D_{TPS} [km]	2	2	Length section between two adjacent TPSs (or L_D)
$D_{TPS-max}$ [km]	3	4	Maximum length section feeding in failure case
n_{TPS} [km]	5	5	Number of traction substations on the line
I_n/TSR [A]	6000	6000	Rated current of a group of rectifiers

Table 7. Condition traction system design.

Component	Value
Running rail UIC 60	0.03 Ω /km/rail, all four rails cross-bonded 0.0075 Ω /km
OCS CuETp 150 + BzII 120	0.0556 Ω /km
3R-Conductor Rail	0.0068 Ω /km, cross-sectional area of 5100 mm ²
ROCS 2214, CuETP 150	0.0119 Ω /km, cross-sectional area of 2202 mm ²
U_n	750 V DC
Working range (U_{min} – U_{max} 1)	525–900 V DC

Table 8. Traction power substation design.

Power	Unit	Segment	Phase 1	Phase 2	Phase 3
P_n	[MW]	L_{TPS}	2.644	2.644	2.644
P_R	[MW]	L_{TPS}	2.227	2.375	2.525
P_{dR}	[MW]	L_{TPS}	2.450	2.612	2.778
P_{fn}	[MW]	D_{TPS}	3.966	3.966	3.966
P_{fR}	[MW]	D_{TPS}	3.341	3.563	3.788
P_{nRE}	[MW]	L_{TPS}	1.584	1.584	1.584
P_{RRE}	[MW]	L_{TPS}	1.470	1.567	1.666
P_{TPS}	[MW/TPS]	D_{TPS}	4.000	4.000	4.000
P_{TSR}	[MW/unit]	D_{TPS}	2.000	2.000	2.000
$P_{RS(150\%)}$	[MW]	D_{TPS}	3.000	3.000	3.000
nP_{TSR}	[MW]	D_{TPS}	2×2.000	2×2.000	2×2.000

Table 9. Minimum $U_{\min}$ -useful at pantograph.

Voltage [V]	Feeding	Distance [km, L = 1 km]			
		L	2 L	4 L	6 L
Un	Single and	750	750	750	750
Umin	Double	500	500	500	500
$U_{\mu\text{-OCS}}$	Single	553.135	497.691		
	Double		720.496	616.549	431.902
$U_{\mu\text{-3R}}$	Single	618.180	584.688		
	Double		742.177	703.276	627.037
$U_{\mu\text{-ROCS}}$	Single	610.908	574.993		
	Double		739.753	693.581	605.224

4. Result and Discussion

According to the proposal of study [11], summarized as follows, analyzing the peak hour coefficients on any day during the survey period resulted in 0.8 described as in Figure 3. This coefficient is included in the next calculation for travel demand according to a 1:1 conversion factor. This is the demand for transportation according to the development cycle in each phase; corresponding to Phase 1 (100%), the result is (De-max-1) 23,676 p/h/d, Phase 2 (150%) is (De-max-2) 35,514 p/h/d, and Phase 3 (200%) is (De-max-3) 47,352 p/h/d. Based on the parameters in Table 2, four types of train control signals are included in the analysis: a three-aspect fixed block (i), cab signal (ii), MVB fixed stopping distance (iii), and MVB variable safety distance (iv). The achieved results are described in Table 3 [11] and Figure 4, in which type (i) has the minimum station headway time and minimum train separation time, being 126.3713 s and 60.2466 s, respectively. Similarly, type (ii) is 113.3310 s and 48.3310 s; type (iii) is 100.0641 s and 35.0641 s; and finally, type (iv) is the smallest at 93.7184 s and 30.2846 s with a variable safety distance MVB system and automatic train operation (ATO) [11]. The simulation and analysis of results on required transport capacity for each stage of each type of train control signal are studied in [11] and summarized in Figure 5. The desired results are expected to meet the greatest transport demand ($D_{e\text{-max}}$) for the PVD MCS line operation plan with maximum service frequency or headways minimum in a variable safety distance moving-block signaling system. The final result chosen is the minimum station running time and the smallest number of trains/hour of 93.7184 s and 38.4129 trains/hour, providing a carrying capacity of 49,937 p/h/d, greater than the necessary demand, which is De-max-3 47,352 p/h/d [11]. They must be rounded to a whole number of trains per hour, i.e., 100 s ($H'_{s(\min)}$)—36 trains per hour ($T'_{s\text{-max}}$), before designing an efficient and accurate traction power source.

With this result, select the train set for the operating plan as shown in Table 4. In Phase 1, operate 100% of transport needs, and train capacity is 658 passengers/train corresponding to a line capacity ($C_{L\text{-max.1}}$) of 23,688 p/h/d (more than $D_{e\text{-max-1}}$ 23,676 p/h/d); in Phase 2, transport demand increases by 150%, and train capacity is 987 passengers/train, corresponding to a $C_{L\text{-max.2}}$ of 35,532 p/h/d (more than $D_{e\text{-max-2}}$ 35,514 p/h/d); and similarly, Phase 3 (200%) is 1320 passengers/train corresponding to ($C_{L\text{-max.3}}$) 47,520 p/h/d (more than $D_{e\text{-max-3}}$ 47,352 p/h/d).

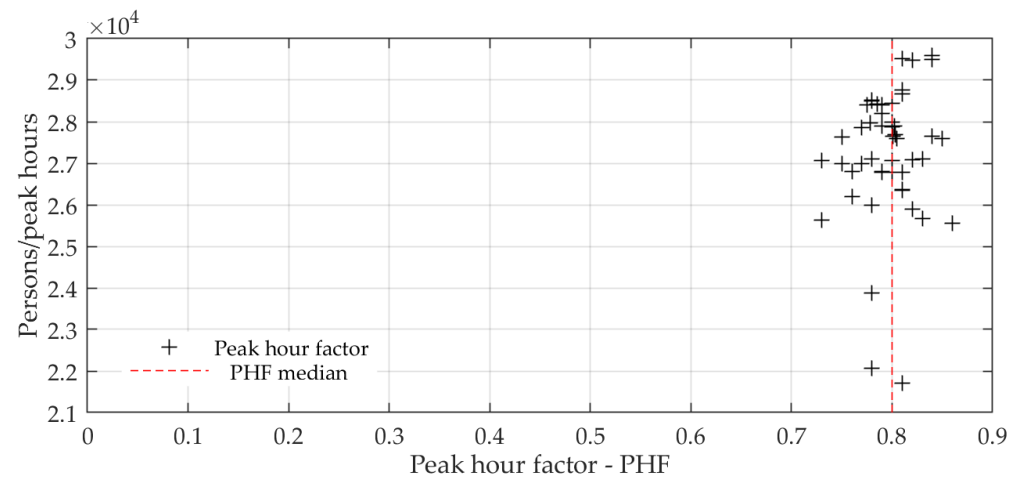


Figure 3. Peak hour factor on PVD line.

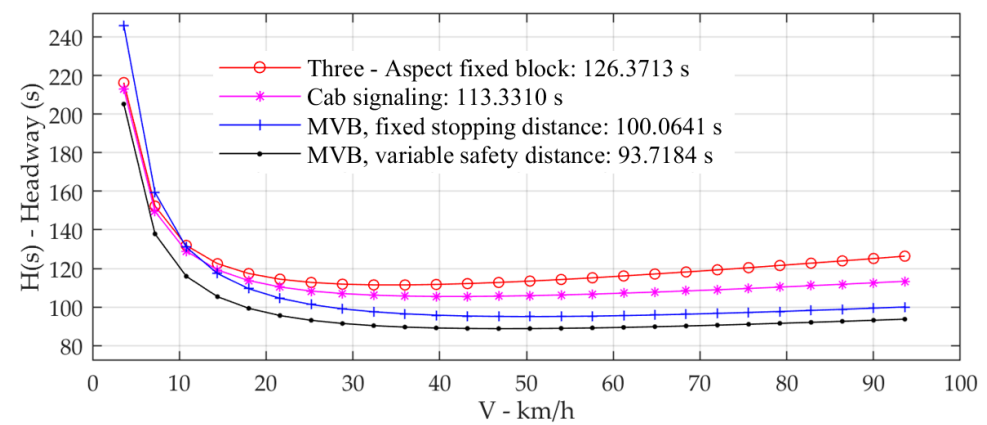


Figure 4. Simulation results of station headway PVD line.

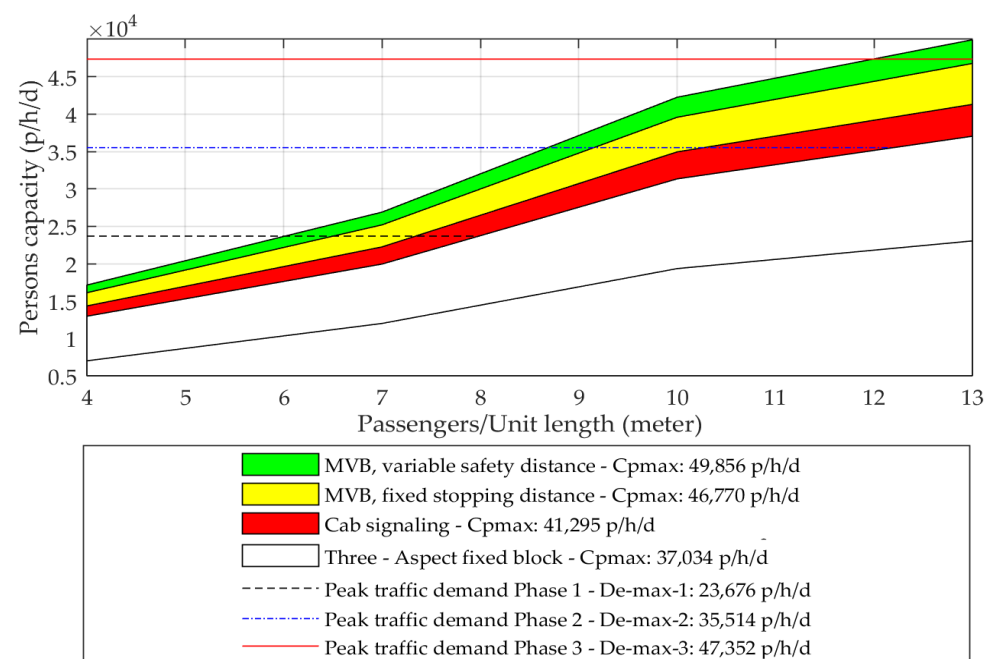


Figure 5. Provide passenger capacity transport in demand of phase on PVD line.

Parameters for traction power supply system design are shown in Tables 5 and 6. Simulation results for all stages and failure scenarios are summarized in Table 7, and a rough description of the system is shown in Figure 6.

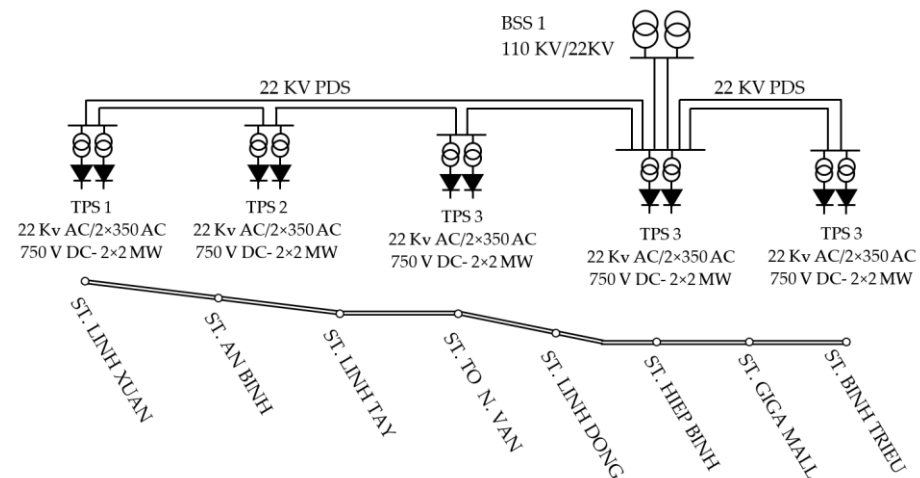


Figure 6. Design and layout of traction power stations on PVD line.

During operation, the aim is to fulfill the requirement of the system with the largest carrying capacity among systems of the same type in each phase. The MCS type, in particular, is characterized by operating with the highest service frequency.

This study is simulated for the power of TPS and compares the values for mean useful voltage (U_{mu}) at the pantograph of the types of contact line systems, OCS, 3R, and ROCS, following single-end feeding and double-end feeding. The results of calculating the required traction power and the minimum values for mean useful voltage at the pantograph under normal operating and failure conditions are given in Tables 7 and 8.

1. Traction power

In Table 8, the calculating result of the power of TPS for three stages of traffic demand in a normal case according to the rated current is 2.644 MW (P_n). In the next step, also calculated according to instantaneous maximum traction force (P_R), the result is 2.227 MW (Phase 1), 2.375 MW (Phase 2), and 2.525 MW in Phase 3. According to traffic demand, with a reserve coefficient of 1.1, the largest capacity in Phase 3 is 2.778 MW (P_{dR}).

In the case of regenerative braking energy recovery, assuming a regenerative recovery system with a maximum capacity of 40%, the minimum power required is from 1.4701 MW to 1.666 MW calculated according to the maximum instantaneous traction force (P_{RRE}), and 1.584 MW calculated according to rated power (P_{nRE}).

In case a failure occurs at any TPS, the two adjacent TPSs before ($i - 1$) and after ($i + 1$) must supply power to the breakdown segment; this time, the power of the TPS ($i - 1$) or TPS ($i + 1$) calculated according to the rated traction current (P_{fn}) is 3.966 MW. The maximum instantaneous power calculated in this case according to the traction force (P_{fR}) for Phases 1, 2, and 3 is 3.341 MW, 3.563 MW, and 3.788 MW, respectively.

Thus, the maximum power of the TPS is chosen to be 4.0 MW (P_{TPS}) with two group rectifiers working in parallel ($n = 2$), each with rated power of 2.0 MW (P_{TSR}). In the normal working mode, one set is working and the other is in standby mode. The supplied power of the TPS in this case (2.0 MW) is larger than the smallest power in the case of the regenerative braking train P_{RRE} (1.6668 MW), but smaller than the largest 2.644 MW and 2.778 MW by 32.2% to 38.9%, corresponding to the overload power of 132% to 138%. However, it is less than the condition allowing continuous overload for two hours, which is 150%. In this case, the selected rated power of TPS meets rated power supply conditions during rush hour.

Considering the fault conditions, at this time, both sets are working simultaneously; the supplied power P_{TPS} is 4.000 MW, which is larger than the instantaneous power

calculated in the fault conditions, which is 3.7882 MW, and approximately, the fault power calculated according to the rated power is 3.9662 MW. Thus, the capacity of the traction substation is greater than the fault condition, meeting the necessary conditions for selecting the capacity of the traction power station with duty level VI according to standards EN 50328, EN 60146-1-1, and IEC 62590, and load limits according to standards NEMA RI9 and IEC 60146-1-1.

2. Useful voltage at pantograph

The TPS's power and the minimum mean useful voltage at the pantograph depend on the length of the power segment and electrical characteristics of the contact line installation. Thus, the longitudinal voltage drops due to the relationship between the contact network resistance and the traction current train, which draws on the power section of TPS. Therefore, considering operating voltage conditions is the next important aspect in the design, based on the traction power distribution single-end feeding or double-end feeding and the following contact line systems: OCS, 3R, and ROCS. Simulation results of U_{mu} in the design, presented in Table 9, are analyzed below.

Involving a single-end feed, under normal operating conditions, and the minimum mean useful voltage at the pantograph when the train appears at the end of each segment ($x = L$), the voltage results in the contact line of each type, OCS, ROCS, and 3R, are 553.135 V, 610.908 V, and 618.180 V, respectively, as shown in Table 9. In the table, the smallest potential at the pantograph in the end section is OCS, 553.135 V; however, this voltage is still greater than the minimum allowable limit standard, being 500 V DC.

Involving a single-end feed, in the case of a breakdown, the maximum segment length of a station that needs to be supplied is $2L = L_D$. When a problem occurs, one group rectifier (2000 MW/RS) in the TPS cannot meet the full load, so two group rectifiers with a total power of 4000 MW must be operated in parallel. This time, the feeding voltage at Z (U_d) is 609.201 V and the voltages in contact line networks for OCS, ROCS, and 3R types are 497.691 V, 574.993 V, and 584.688 V, respectively, Table 9 and Figure 7. In these, the useful voltage at the pantograph on OCS is 497.691 V, and this potential is smaller than the minimum limit allowed, being 500 V DC, as shown in Figure 7. In this case, the voltage in the contact line on the ROCS network still ensures an operating voltage of 574.993 V, greater than the U_{n-min} value.

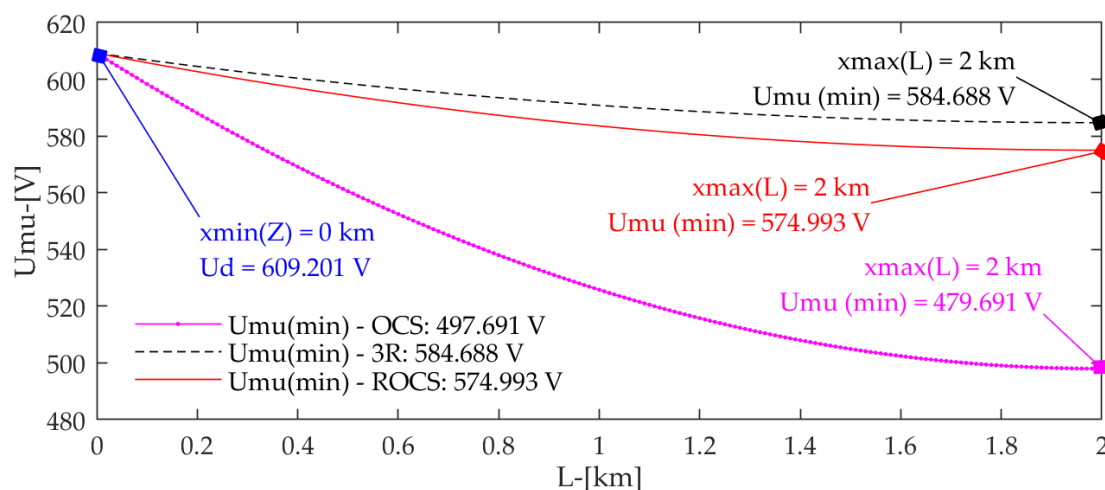


Figure 7. Minimum U_{mu} at pantograph in single-end feed in case of fault.

Involving a double-end feed, with the distance between the two TPSs (i) and ($i + 1$) being $2L = L_D$ under normal operating conditions, the minimum mean useful voltage at the pantograph is $x = L_D/2$. The simulated result of the feeding voltage at Z (U_d) is 748.311 V and the voltage in contact line networks for OCS is 720.496 V; on the ROCS contact network system, it is 739.753 V; and on the 3R system, it is 742.177 V, as shown in

Figure 8. Thus, in the case of a double-end feed, the smallest voltage in the contact line on all three types of contact networks meets the operating voltage conditions.

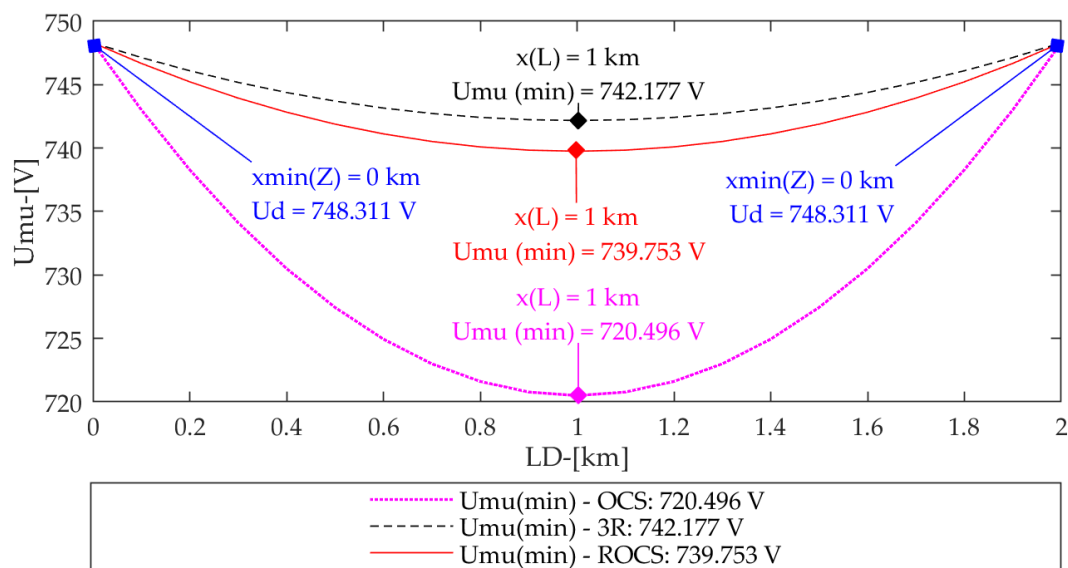


Figure 8. Minimum U_{μ} at pantograph in double-end feed with distance length of $2 L$.

Similarly, regarding the simulation results, the distance length between two TPSs, (i) and (i + 1), is $2 L_D$. The result simulates the minimum mean useful voltage at the pantograph at $x = L_D$. This time, the voltage results in the contact line of each type, OCS, ROCS, and 3R, are 616.549 V, 693.581 V, and 703.276 V, respectively, as shown in Figure 9. In this scenario, the smallest potential at the pantograph at the end section of OCS is 616.549 V; however, this voltage is still greater than the minimum allowable limit standard, which is 500 V DC, and even greater than 553.135 V on an OCS single-end feed with $x = L$. Thus, in the case of a double-end feed, with the distance length being $2 L_D$, the smallest voltage in the contact line on all three types of contact networks meets the operating voltage conditions.

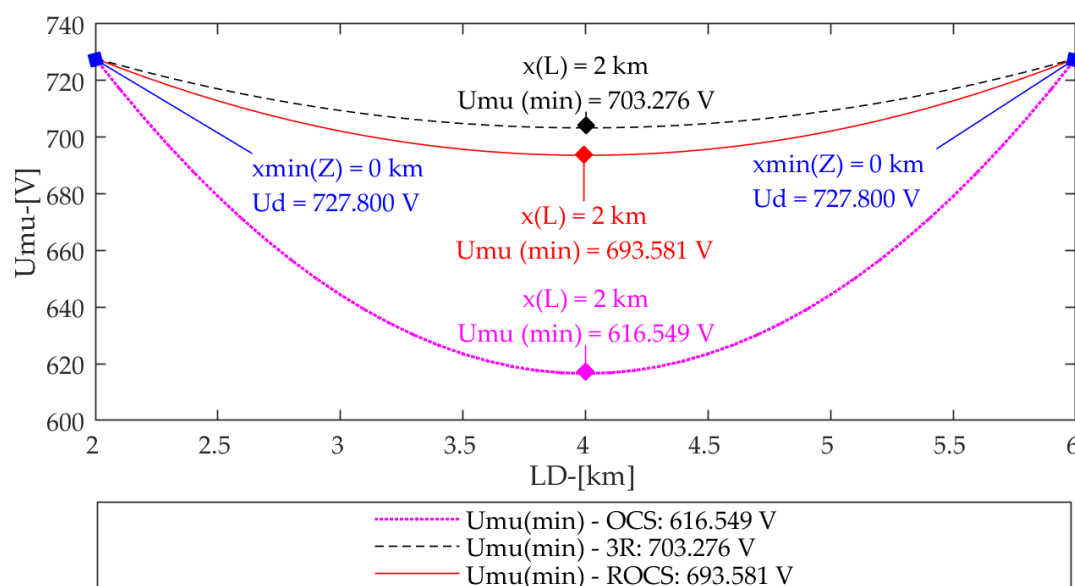


Figure 9. Minimum U_{μ} at pantograph in double-end feed with distance length of $4 L$.

Suppose we increase the simulation distance between two TPSs, (i) and (i + 1), to $3 L_D$, in the case of a power supply with double-end feeding. The simulated result of the feeding voltage at Z (U_d) is 682.208 V and the voltage in contact line networks for OCS is 431.902 V;

on the ROCS contact network system, it is 605.224 V; and on the 3R system, it is 627.037 V, as shown in Figure 10. In this case, the useful voltage at the pantograph on OCS is the smallest at 431.902 V; this potential is smaller than the minimum limit allowed, being 500 V DC, but the voltage in the contact line using the ROCS network still ensures an operating voltage of 605.902 V, greater than the U_{n-min} value (500 V).

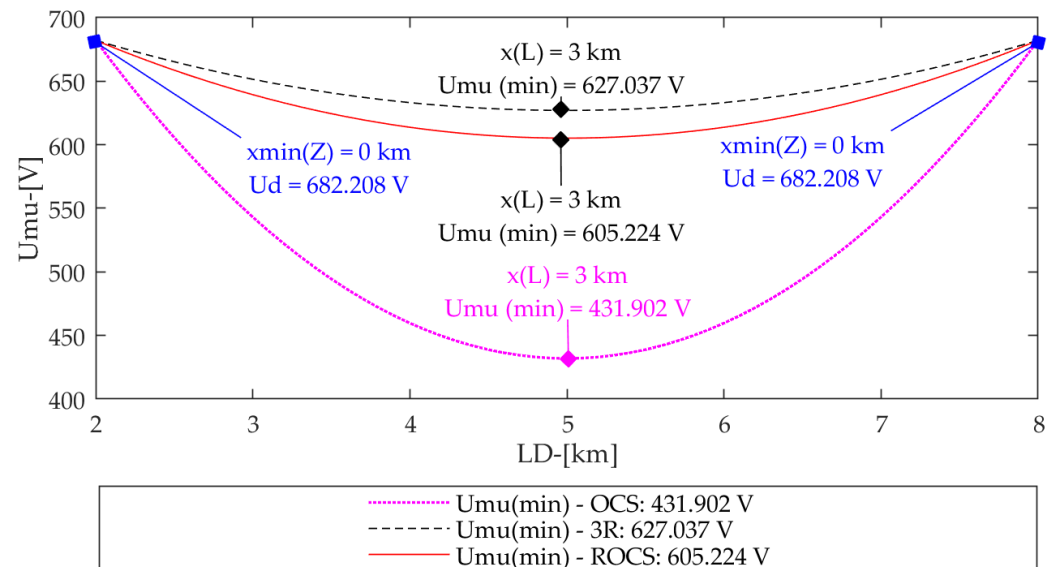


Figure 10. Minimum U_{mu} at pantograph in double-end feed with distance length of 6 L.

In summary, the result is calculated from the power supply design for the MCS PVD line for the contact network using the new ROCS conductive rails, and whether the power supply is from one direction or two directions, the minimum values for mean useful voltage at the pantograph always meet the requirements' forecast for PVD line operation and satisfy the above design requirements.

5. Conclusions

This article presents the results of research on the feasibility of providing traction power for a new type of transport in a modern urban railway transport system. This study delves into different scenarios, from increased traffic demand to supply and operating voltage on contact line network systems. Research results show that the minimum mean useful voltage value at the pantograph on the ROCS always meets all possible assumptions in segment length selection power and hypothetical operating situations. In particular, the application of ROCS in design is a unique discovery for synchronizing the contact line system, leading to a comprehensive integrated solution in the urban railway system.

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