A Research on Passenger Carrying Capacity of an Innovative Electric Traction Power Supply System based on ROCS of 750 V DC MRT

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ABSTRACT

This article presents the results of a study on the feasibility of a Rigid Overhead Conductor-rail System (ROCS) for a Mass Rapid Transit (MRT) system using 750 V DC power based on a carrying capacity transport-supply voltage level relationship. In particular, peak load conditions often cause serious problems of voltage drops occurring along the contact line, affecting the reliability, flexibility, system safety, and efficiency performance of the MRT system. The potential at the pantograph of a train on the segment of power supply depends significantly on the structure of the traction power supply network, contact network type, and voltage level. Recently, there have been studies on the dynamics of ROCSs under the impact of train motion, thereby applying the design to several railway systems in the world in specific conditions such as tunnels, stations, or viaducts. To consolidate the advantages of this trend, this paper studies the operating voltage of an ROCS in a full-line MRT system with a voltage level of 750 V DC belonging to the third rail. Matlab R2017b/Railway Systems is a reliable software for simulating and analyzing the necessary data. The results exhibit the feasibility of the designed ROCS. The system has a passenger carrying capacity of up to 90,000 passengers per hour per direction (p/h/d) under both normal and fault conditions. In this case, this capacity is achieved with a single-end feed at a distance of 2 km from a Traction Power Station (TPS), with the minimum feeder voltage at the pantograph point being 532.7200 V. The lowest operational feeder voltage of the system is 523.6667 V, supplied from a double-end feed at a distance of up to 5 km from the TPS.

Keywords-mass rapid transit; Rigid Overhead Conductor (ROC); third rail system; overhead contact system; 750 V DC third rail

I. INTRODUCTION

Traditionally, in the design of the power supply of subway train traction, there is a strong correlation between route capacity and voltage, effectively becoming a "dual standard" with specific guidelines. In the simplest traction circuit, consisting of a voltage source U, wire resistor r, and traction load R, the traction current in the circuit is determined according to Ohm's law, and the voltage drop along the contact line is caused by the contact wire resistor and the total value of the instantaneous traction current. Currently, the contact line system is using an Overhead Contact System (OCS) and a third rail system. Specifically, 750 V DC traction systems are built for medium capacity Mass Rapid Transit (MRT), from 20,000 passengers per hour per direction (p/h/d) to 40,000 p/h/d, or at the most cater to the peak traffic maximum up to 48,000 p/h/d. Over 58% of the subways have been commissioned with a third rail system out of which less than even 1% is networked with the OCS. A review of the data available for MRT systems indicates that a 1,500 V DC system has been selected for a designed carrying capacity from 40,000 p/h/d to 64,000 p/h/d to a maximum up to 75,000 p/h/d, and is designated as an overhead contact network [1-6].

In recent times, ROCSs have been widely applied in urban railway projects in limited locations, such as tunnels, viaducts, level crossings, stations, or some subway lines or light rail transit [7-9]. However, specific research on the correlation between operating voltage level and passenger carrying capacity is almost non-existent, internal, and monotonous [10].

Therefore, studying the technical feasibility of a 750 V DC traction system deploying ROCS and its relationship with the peak-hour traffic is necessary. This study evaluates the carrying capacity when utilizing ROCS, which is a new basis for the widespread application of ROCS in power supply design for subways. Most studies in the design of electric traction power supply for subway trains involve comprehensive simulations, which are efficient, and cost-effective. In this research, Matlab R2017b/Railway Systems is the chosen software for simulating calculations in the power supply design. It is used in the form of writing scripts (code) according to a series of calculation formulas, which are suitable for the general application scenario presented in this article [11-12].

II. DESCRIPTION OF ROCS

A. Introducing ROCS

ROCS is an overhead line system that can substitute traditional overhead lines (carrying cable and contact wire), conductor rail, and suspended rail systems successfully, with an installation structure depicted in Figures 1 and 2. This system comprises a treated aluminium body, in a clamp shape that holds the copper contact wire in place, providing greater stiffness and greater circuit section, which allows the removal of parallel conductor cables at 750 V – 1,500 V DC and permits voltages up to 25 kV AC. It is used as a replacement for third rail contact networks or flexible overhead line contact. It allows smaller tunnel cross-sections for new constructions, lower support columns and replacement electrification of tunnels and stations originally built for the third rail system, and offers high electrical cross-sections, so that additional feeders can be avoided, whereas its fire resistance is significantly greater than that of a catenary system. It is characterized by faster installation and less electrical risks, installation time, costs, and rolling stock maintenance than when employinmg the third rail system [7-10].

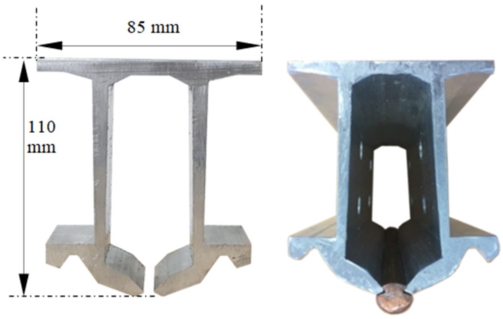

Fig. 1. Cross-section of conductor rail.

B. Conductor Support Profile

The conductor support profile comprises many different parts. The following list summarizes its main components [7-10]: It is manufactured by extrusion in 6106 T5 aluminium alloy, thermally treated, according to BS EN 573-3:2009, in lengths of 10 m or 12 m, or lower depending on the assembly conditions. Conductor-rail profiles are joined by using pairs of interlocking joints. The groove and rib system between the conductor-rail profile and the interlocking joint ensures that the joints are formed free of any kink. At the same time, it ascertains optimum current transfer due to the numerous single-point and continuous linear contacts between the profile section and the interlocking joints. The bottom of the profile is shaped like a clamp in which the contact wire is held in place. The profile can be manufactured with two heights, typically 110 mm and 80 mm, depending on the existing gauges, and cross sections, which are 2,202 mm^2 and 2,223 mm^2. The main characteristics of the aluminium profile for those two heights can be seen in Table I.

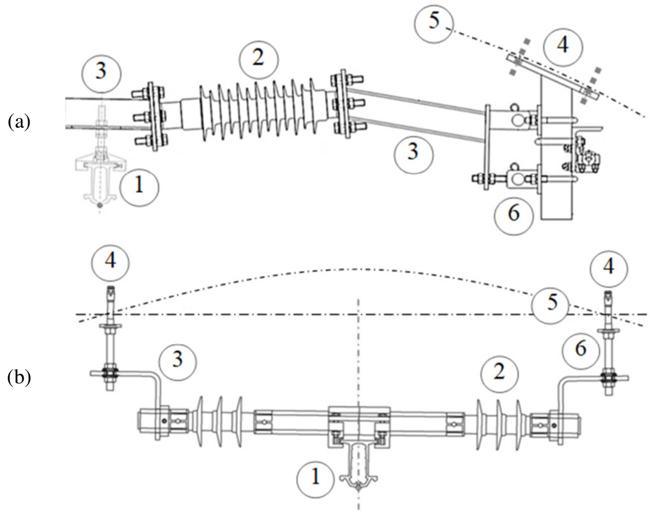

Fig. 2. Installation structure ROCS: (a) Busbar support bracket, (b) crossbar, where: (1) conductor bar, (2) insulator, (3) support bracket/hanging mechanism, (4). Anchor bolt, (5) Vault/arch suspension, and (6) height limit.

TABLE I. GENERAL TECHNICAL DATA OF ROCS

Component	Unit	Value
Rated voltage DC	[V]	750 ÷ 3,000
Continuous current	[A]	2,000 ÷ 4,000
Short circuit current	[kA]	40 during 60 ms
Ambient temperature	[^{0}C]	– 40
Max. conductor temperature	[^{0}C]	90
Max. distance between support structures	[m]	14
Conductor-rail height	[mm]	80, 110, 130
Conductor-rail cross-section	[mm^2]	2,200 ÷ 2,400
Contact wire used EN 50149	[mm^2]	80 ÷ 161
Conductor-rail material		Aluminum alloy
Weight	[kg/m]	5.7 ÷ 6.1

The structure includes the following components: conductor rail, conductor inter-locking joints, union plate, support and clamps, movable arms, transition element, electrical connection clamp, anti-creep clamps, earth clamps, protection cover, joint and end cap, cable connection source, and insulator [7-10].

III. SYSTEM DESIGN

A. Load Calculation Method

The maximum passenger carrying capacity of the route at each phase is determined based on the relationship between the headway or the number of trains per hour in the direction and the carrying capacity of each train. In the MRT, it is considered that the load is evenly and uniformly distributed, the parameters of the source and contact network are constant, and the voltage drops on each contact line segment due to the passing trains appearing on them. With the above assumptions, the number of trains on each supply segment of a traction power station is determined in the following cases [1, 3-4]:

$$n^{n}_{tps(i)} = \frac{3600}{H_s} \times \frac{1}{v_{sc}} \times D_{tps(i)},\ \forall n^{n}_{tps(i)} \geq 1 \quad (1)$$

$$n^{er}_{tps(i)} = \frac{3600}{H_s} \times \frac{1}{v_{sc}} \times \left(D_{tps(i)} + \frac{D_{tps(i+1)}}{2}\right),\ \forall n^{er}_{tps(i)} \geq 1 \quad (2)$$

$$x^{n}_{tps(i)} = \frac{3600}{H_s} \times \frac{1}{v_{sc}} \times l_{x<Dtps(i)},\ \forall x^{n}_{tps(i)} \geq 1 \quad (3)$$

where $n^{n}_{tps(i)}$ is the number of trains appearing in a segment of a TPS, $n^{er}_{tps(i)}$ is the number of trains in a segment of a TPS in case of a breakdown, $n^{n}_{tps(i)}$ is the number of trains in the segment at any x, with $l_x < D_{tps}$, D_{tps} is the distance between two TPSs, v_{sc} is the schedule train speed, l_x is the distance from a TPS to any position x, and H_s is the headway.

As the TPS supplies the double tracks, 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 [1, 10, 12-17]:

$$U_n = U_{d0} - I_{tr} \times n^{cse}_{t(tpsi)} \times \sum R_0 \quad (4)$$

where I_{tr} is the rate current traction per train, $n^{cse}_{t(tpsi)}$ represents the total of the trains in each feed section considering normal or fault operation, and R_0 is the 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 [13-17]:

$$\Delta U_x = R_{trac} \times \sum_{j=1}^{m_t} I_{tr.j} \times x_j \quad (5)$$

$$\Delta U_{max:x_{mt} \to L} = R_{trac} \times \left[\sum_{j=1}^{m_t - 1} I_{tr.j} \times x_j + I_{tr.mt} \times L\right] \quad (6)$$

$$\Delta U_{x,\ cond:\ x<L} = \frac{1}{L} \times R_{trac} \sum_{j=1}^{m_t} I_{tr.j} \times \int_0^x (L-x)dx \quad (7)$$

$$\Delta U_{x,\ cond: x<L} = \frac{1}{L} \times R_{trac} \times \sum_{j=1}^{m_t} I_{tr.j} \times \left(L \times x - \frac{x^2}{2}\right) \quad (8)$$

The ΔU_{max} maximum voltage drop is [15-17]:

$$\Delta U_{max:x \to L} = \frac{1}{L} \times R_{trac} \times m_t \times I_{tr} \times \left(L \times x - \frac{x^2}{2}\right) \quad (9)$$

where R_{trac} is the loop resistance per unit length (Ω/km), m_t represents a train in a feed section, and x is the distance from the feed. In (9), the maximum voltage drop when a train occurs 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 $L_D = 2 \times L$. It is presumed that $U_{d(i)} = U_{d(i+1)} = U_d$ and that $R_{0\ (i,\ i+1)}$ are constant between all TPSs. Assuming there is one train moving between two TPSs, (i) and (i+1), at position x, the total traction current is supplied from both adjacent TPSs [15-17]. If TPS(i) is a reference point, the maximum voltage drop ΔU_{max} will occur at the point $x = L_D/2$:

$$I_{tr(x)} = I_{t(i)} + I_{t(i+1)} \quad (10)$$

$$\Delta U_{x\ (i)} = x \times R_{trac} \times I_{t(i)} \quad (11)$$

$$\Delta U_{x\ (i+1)} = (L_D - x) \times R_{trac} \times I_{t(i+1)} \quad (12)$$

$$I_{t(i)} = I_{tr} \times \left(1 - \frac{x}{L_D}\right) \quad (13)$$

$$I_{t(i+1)} = I_{tr} \times \left(\frac{x}{L_D}\right) \quad (14)$$

(13) and (14) can be rewritten for several trains [15-17]:

$$I_{t(i)} = I_{tr(1)} \times \left(1 - \frac{x_1}{L_D}\right) + \ldots + I_{tr(mt)} \times \left(1 - \frac{x_{mt}}{L_D}\right)$$

$$= \sum_{j=1}^{m_t} I_{trj} \times \left(1 - \frac{x_j}{L_D}\right) \quad (15)$$

$$I_{t(i+1)} = I_{tr(1)} \cdot \left(\frac{x_1}{L_D}\right) + \ldots + I_{tr(mt)} \times \left(\frac{x_{mt}}{L_D}\right) = \sum_{j=1}^{m_t} I_{trj} \times \left(\frac{x_j}{L_D}\right) \quad (16)$$

$$\Delta U_{(i),\ max:\ x \to L_D/2} = x \times R_{trac} \times \left(I_{t(i)} + I_{t(i+1)}\right) \times \left(1 - \frac{x}{L_D}\right) \quad (17)$$

Assuming three trains are moving between TPS (i) and TPS (i+1), the voltage drop at position x_2 is [15-17]:

$$\Delta U_{(i)2} = R_{trac} \times \left[\frac{I_{tr1} \times x_1}{L_D} \times (L_D - x_2) + \frac{I_{tr2} \cdot x_2}{L_D} \times (L_D - x_2) + \frac{I_{tr3} \times x_2}{L_D} \times (L_D - x_3)\right] \quad (18)$$

From (18), and for the k[th] train at point x, we have:

$$\Delta U_{(i)x} = \frac{R_{trac}}{L_D} \times \left[(L_D - x_{(i)k}) \times \sum_{j=1}^{k} I_{trj} \times x_{(i)j} + x_{(i)j} \times \sum_{j=k+1}^{m_t} I_{trj} \times (L_D - x_{(i)j})\right] \quad (19)$$

$$\Delta U_{x,\ cond:\ x<\frac{L_D}{2}} = \frac{R_{trac}}{L_D} \times \sum_{j=1}^{m_t} I_{tr.j} \times \int_0^x \left(\frac{L_D}{2} - x\right) dx \quad (20)$$

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

The maximum voltage drop ΔU_{max} occurs when $x = L_D/2$ [15-17]:

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

The minimum voltage in the contact line at the train drawing current at the end section for each operating condition is written as:

$$U^{f}_{tr\text{-}min} = U_n - \Delta U^{f}_{max} \quad (23)$$

Finally, the minimum values for mean useful voltage at the pantograph under normal operating conditions $U^{f}_{tr\text{-}min} = U_{mu}$ must adhere to EN 50163 and several related standards.

B. Load Parameters

The study was carried out on a hypothetical route similar to the North–South Line (NSL, line length 45 km) a high-capacity MRT line in Singapore. The line operates for almost 20 hours every day (from the first departure of 5:07 am to approximately 1 am the next day), with headways of up to 1 to 2 min during peak hours and 5 to 8 min during off-peak hours. All trains on the NSL run in a six-car formation of the Alstom Movia R151 series.

IV. SIMULATION RESULTS

The basic parameters of the train are described in Table II and the parameters necessary for contact line system simulation can be detected in Table III. Two designs were simulated: single-end feed and double-end feed. The research results of the considered scenarios (cases) are portrayed in Tables IV and V.

TABLE II. TRAFFIC CAPACITY PARAMETERS AT PEAK HOURS

System load parameters		
Component	**Unit**	**Value**
Electrification system	[V DC]	750
Route length	[km]	45
Number of ST	[xi]	40
Headways 180 seconds	[p/h/d]	38,400 – 40,000
Headways 150 seconds	[p/h/d]	46,080 – 48,000
Headways 120 seconds	[p/h/d]	57,600 – 60,000
Headways 100 seconds	[p/h/d]	69,120 – 72,000
Headways 90 seconds	[p/h/d]	76,800 – 80,000
Headways 80 seconds	[p/h/d]	86,400 – 90,000
Acceleration/ Deceleration	[m/s^2]	1.0/1.2
Maximum speed/ schedule speed	[km/h]	80/36
Trainset	[car]	6
Capacity of train (passenger/train)	[p/tr]	1,920 – 2,000
Train configuration UIC		2'2'+4×Bo'Bo'+2'2'
Train output power	[MW]	2.24
Rated power of rectifier group	[MW]	5.000
Maximum current of rectifier group	[A]	6,666

TABLE III. TRACTION SYSTEM PARAMETERS

Component	Unit	Value
Nominal Voltage DC	[V]	750
ROCS 2214, CuETP 150	[A]	4,000
ROCS 2214, CuETP 150	[Ω/km]	0.0119 (single track)
Rail UIC60 20^0C	[Ω/km]	0.03 (single track)
Cable DC 100 m, 500 mm^2	[Ω]	0.0015

A. *Single-end Feed*

In Case 3, the power supply radius of each TPS is 1 km and the headways range from 180 s to 80 s. It is assumed that during peak hours the number of trains appearing on each radius segment of power ranges from 0.56 to 1.25 trains, the line's maximum carrying capacity ranges from 86,400 to 90,000 p/h/d, and the minimum value for mean useful voltage at the pantograph (U_{mu-min}) is 713.7867 V. If a fault that disables the power supply of any TPS occurs, the power supply range of an adjacent station is 3 km in both directions, and the longest segment of power is 2 km. In this case, with a headway of 80 s, the carrying capacity of the line with the selected configuration is 86,400 p/h/d to 90,000 p/h/d, the U_{mu} is 532.7200 V, which is greater than $U_{mu\ -\ min}$, which is 500 V. The TPS is allowed to overload up to 145.5% at the headways of 80 s, during this time. The U_{mu-min} is 500.1 V meeting the 500 V DC according to EN 50163 standard, as manifested in Figure 3. In Case 2, when the power supply radius of each TPS is 2 km, with headways of 180 s to 80 s, and the total number of trains appearing on the feeding segment of each TPS ranges from 4.444 to 10, the maximum carrying capacity on the line ranges from 86,400 to 90,000 p/h/d. However the smallest U_{mu} is 605.1467 V. If a failure disables the power supply of any TPS, the adjacent TPS power supply range is 6 km, and the largest feeding segment will be 4 km (Case 4). At this time, in all cases, the headways decrease from 180 s to 80 s, and the maximum U_{mu} ranges from 492.4830 V to 170.5867 V, both values being below the 500 V limit.

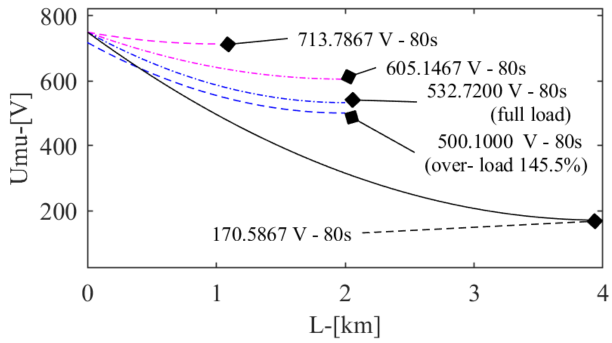

Fig. 3. The minimum U_{mu} in Case 3 of single - end feed.

Thus, when single-end feeding of the system using ROCS is utilized, only Case 1 with R_{TPS} = 1 km (D_{TPS} = 2 km) is capable of working in both normal and emergency cases (Case 3, $R_{TPS-max}$ = 2 km) with the appropriate carrying capacity, and can reach up to 90,000 p/h/d with headways reaching 80 s.

B. *Double – End Feed*

When supply is provided from both ends, the distance between two TPSs will change to 4 km, 5 km, and 6 km and the peak hour headways are 180 s to 80 s for each case respectively, as can be seen in Table V and Figure 4. In Case 1, the D_{TPS} distance is 4 km, with headways of 80 s, carrying capacity up to 90,000 p/h/d, U_{mu-min} equal to 605.1467 V. Similarly, in Case 2, the distance between two TPSs increases to 5 km with a maximum headway of 80 s, and the smallest U_{mu} is 523.6667 V, larger than the minimum voltage of 500 V DC. In Case 3, when the distance is augmented up to 6 km, it can only meet headways of 120 s. At this time the U_{mu-min} is 532.7200 V. Simulation results also demonstrate that with headways of 100 s to 80 s with a distance of 6 km, the maximum U_{mu} changes from 489.2640 V down to 420.0800 V, all less than the limit of 500 V DC.

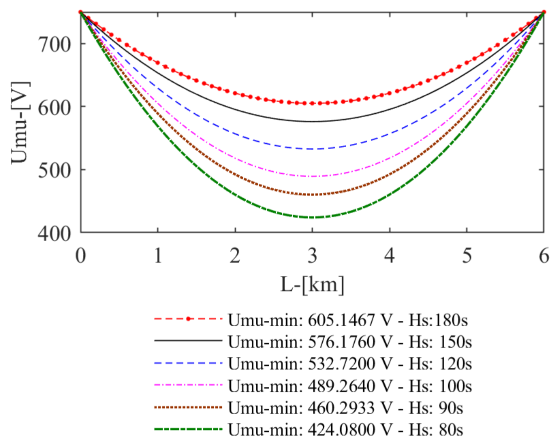

Fig. 4. U_{mu-min} of Case 3 of double - end feed.

Thus, in the case of double – end feed, the distance of the TPSs can be up to 5 km, with the train capacity chosen for simulation to meet headways up to 80 s, the carrying capacity of the line being up to 90,000 p/h/d, and a $U_{mu\text{-}min}$ of 523.6667 V, greater than 500 V DC.

TABLE IV. DESIGN RESULTS FOR 750 V DC SINGLE END FEED

CASE	R_{TPS}	Hs	C_t	CL_{max}	t/D_{TPS}	$U_{dc\text{-}0}$	$U_{n\text{-}dc}$	P_{TPS}	I_{tr}	ΔU	$U_{mu\text{-}min}$
	[km]	[s]	[p/tr]	[p/h/d]	[train]	[V]	[V]	[MW]	[A]	[V]	[V]
CASE 1	1	180	1,920 – 2,000	38,400 – 40,000	4.0000	824.990	750	2×5+5.0	2,986.667	28.9707	721.0293
		150	1,920 – 2,000	46,080 – 48,000	4.0000	824.990	750	2×5+5.0	2,986.667	28.9707	721.0293
		120	1,920 – 2,000	57,600 – 60,000	4.0000	824.990	750	2×5+5.0	2,986.667	28.9707	721.0293
		100	1,920 – 2,000	69,120 – 72,000	4.0000	824.990	750	2×5+5.0	2,986.667	28.9707	721.0293
		90	1,920 – 2,000	76,800 – 80,000	4.4444	824.990	750	2×5+5.0	2,986.667	32.1896	717.8104
		80	1,920 – 2,000	86,400 – 90,000	5.0000	824.990	750	2×5+5.0	2,986.667	36.2133	713.7867
CASE 2	2	180	1,920 – 2,000	38,400 – 40,000	4.4444	824.990	750	2×5+5.0	2,986.667	64.3793	685.6207
		150	1,920 – 2,000	46,080 – 48,000	5.3333	824.990	750	2×5+5.0	2,986.667	77.2551	672.7449
		120	1,920 – 2,000	57,600 – 60,000	6.6667	824.990	750	2×5+5.0	2,986.667	96.5689	653.4311
		100	1,920 – 2,000	69,120 – 72,000	8.0000	824.990	750	2×5+5.0	2,986.667	115.8827	634.1173
		90	1,920 – 2,000	76,800 – 80,000	8.8889	824.990	750	3×5+5.0	2,986.667	128.7585	621.2415
		80	1,920 – 2,000	86,400 – 90,000	10.000	824.990	750	3×5+5.0	2,986.667	144.8533	605.1467
CASE 3	1+2	180	1,920 – 2,000	38,400 – 40,000	3.3333	824.990	750	2×5+5.0	2,986.667	72.0089	686.1778
		150	1,920 – 2,000	46,080 – 48,000	4.0000	824.990	750	2×5+5.0	2,986.667	91.3227	658.6773
		120	1,920 – 2,000	57,600 – 60,000	5.0000	824.990	750	2×5+5.0	2,986.667	120.2933	617.4267
		100	1,920 – 2,000	69,120 – 72,000	6.0000	824.990	750	2×5+5.0	2,986.667	149.2640	576.1760
		90	1,920 – 2,000	76,800 – 80,000	6.6667	824.990	750	2×5+5.0	2,986.667	168.5778	556.8622
		80	1,920 – 2,000	86,400 – 90,000	7.5000	824.990	750	2×5+5.0	2,986.667	192.7200	532.7200
CASE 4	2+2	180	1,920 – 2,000	38,400 – 40,000	6.6667	824.990	750	2×5+5.0	2,986.667	257.5170	492.4830
		150	1,920 – 2,000	46,080 – 48,000	8.0000	824.990	750	2×5+5.0	2,986.667	309.0204	440.9796
		120	1,920 – 2,000	57,600 – 60,000	10.0000	824.990	750	3×5+5.0	2,986.667	386.2756	363.7244
		100	1,920 – 2,000	69,120 – 72,000	12.0000	824.990	750	3×5+5.0	2,986.667	463.5307	286.4693
		90	1,920 – 2,000	76,800 – 80,000	13.3333	824.990	750	4×5+5.0	2,986.667	515.0341	234.9659
		80	1,920 – 2,000	86,400 – 90,000	15.0000	824.990	750	4×5+5.0	2,986.667	579.4133	170.5867

TABLE V. DESIGN RESULT 750 V DC DOUBLE – END FEED

CASE	D_{TPS}	Hs	C_t	CL_{max}	t/D_{TPS}	$U_{dc\text{-}0}$	$U_{n\text{-}dc}$	P_{TPS}	I_{tr}	ΔU	$U_{mu\text{-}min}$
	[km]	**[s]**	**[p/tr]**	**[p/h/d]**	**[train]**	**[V]**	**[V]**	**[MW]**	**[A]**	**[V]**	**[V]**
CASE 1	4	180	1,920 – 2,000	38,400 – 40,000	4.4444	824.990	750	2×5+5.0	2,986.667	64.3793	685.6207
		150	1,920 – 2,000	46,080 – 48,000	5.3333	824.990	750	2×5+5.0	2,986.667	77.2551	672.7449
		120	1,920 – 2,000	57,600 – 60,000	6.6667	824.990	750	2×5+5.0	2,986.667	96.5689	653.4311
		100	1,920 – 2,000	69,120 – 72,000	8.0000	824.990	750	2×5+5.0	2,986.667	115.8827	634.1173
		90	1,920 – 2,000	76,800 – 80,000	8.8889	824.990	750	3×5+5.0	2,986.667	128.7585	621.2415
		80	1,920 – 2,000	86,400 – 90,000	10.000	824.990	750	3×5+5.0	2,986.667	144.8533	605.1467
CASE 2	5	180	1,920 – 2,000	38,400 – 40,000	5.5556	824.990	750	2×5+5.0	2,986.667	100.5926	649.4074
		150	1,920 – 2,000	46,080 – 48,000	6.6667	824.990	750	2×5+5.0	2,986.667	120.7111	629.2889
		120	1,920 – 2,000	57,600 – 60,000	8.3333	824.990	750	2×5+5.0	2,986.667	150.8889	599.1111
		100	1,920 – 2,000	69,120 – 72,000	10.000	824.990	750	3×5+5.0	2,986.667	181.0667	568.9333
		90	1,920 – 2,000	76,800 – 80,000	11.1111	824.990	750	3×5+5.0	2,986.667	201.1852	548.8148
		80	1,920 – 2,000	86,400 – 90,000	12.5000	824.990	750	3×5+5.0	2,986.667	226.3333	523.6667
CASE 3	6	180	1,920 – 2,000	38,400 – 40,000	6.6667	824.990	750	2×5+5.0	2,986.667	144.8533	605.1467
		150	1,920 – 2,000	46,080 – 48,000	8.0000	824.990	750	2×5+5.0	2,986.667	173.8240	576.1760
		120	1,920 – 2,000	57,600 – 60,000	10.0000	824.990	750	3×5+5.0	2,986.667	217.2800	532.7200
		100	1,920 – 2,000	69,120 – 72,000	12.0000	824.990	750	3×5+5.0	2,986.667	260.7360	489.2640
		90	1,920 – 2,000	76,800 – 80,000	13.3333	824.990	750	4×5+5.0	2,986.667	289.7067	460.2933
		80	1,920 – 2,000	86,400 – 90,000	15.0000	824.990	750	4×5+5.0	2,986.667	325.9200	424.0800

V. CONCLUSION

The in-depth analysis results of the relationship between the carrying capacity and the minimum average value of voltage in contact networks using new ROCS conductive rails under longitudinal voltage drop conditions when the carrying capacity increases satisfies several operating conditions of voltage on the new contact line. It also discloses that ROCS is feasible for application in a contact line network design of a 750 V DC MRT system under many different scenarios. It is possible to standardize ROCS design synchronously across the line and not only in a limited number of locations. The research results form a reliable scientific basis of the technical characteristics profile of ROCS acting as a reference for countries that are planning MRT networks due to its advantages in comparison with the two types of traditional contact line systems.

REFERENCES

[1] D. D. Van, N. Thai, and L. X. Hong, "An In-Depth Investigation of Innovative Electric Traction Power Supply Systems for Mass Rapid Transit," *Engineering, Technology & Applied Science Research*, vol. 13, no. 6, pp. 12245–12252, Dec. 2023, https://doi.org/10.48084/etasr.6447.

[2] *Report of the Sub-Committee on Traction Systems, General Power Supply Arrangements and Energy Efficient Systems for Metro Railways*. New Delhi, India: Government of India Ministry of Urban Development, 2013.

[3] D. D. Van, "A Research on the Load Calculation Method in Designing the Traction Power Supply for Integrated Subway – MCR," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10882–10887, Jun. 2023, https://doi.org/10.48084/etasr.5909.

[4] D. D. Van, "A Research on the Load Calculation Method in Designing the Traction Power Supply for Integrated Subway – MCR," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10882–10887, Jun. 2023, https://doi.org/10.48084/etasr.5909.

[5] F. A. A. Rahman, M. Z. A. A. Kadir, M. Osman, and U. A. U. Amirulddin, "Review of the AC Overhead Wires, the DC Third Rail and the DC Fourth Rail Transit Lines: Issues and Challenges," *IEEE Access*, vol. 8, pp. 213277–213295, 2020, https://doi.org/10.1109/ACCESS.2020.3040018.

[6] H. Mishra, R. Gnanavignesh, and G. Narayanan, "Review of Traction Standards and Simulation of Traction Power Supply System," in *2022 IEEE India Council International Subsections Conference (INDISCON)*, Bhubaneswar, India, Jul. 2022, pp. 1–6, https://doi.org/10.1109/INDISCON54605.2022.9862868.

[7] X. Liu *et al.*, "Effect of different gaps in the conductor rail joints on the current-carrying wear performance of carbon skateboards/conductive rail contact," *Wear*, vol. 536–537, Jan. 2024, Art. no. 205172, https://doi.org/10.1016/j.wear.2023.205172.

[8] X. Feng, Z. Hu, S. Gao, F. Duan, W. Chu, and Y. Song, "Modelling and Analysis of Expansion Joints' Effect on Dynamic Performance of Railway Rigid Overhead System," *Sensors*, vol. 23, no. 15, Jan. 2023, Art. no. 6797, https://doi.org/10.3390/s23156797.

[9] S. Strano, M. Terzo, and C. Tordela, "Multipurpose model for pantograph dynamic interaction with flexible or rigid catenary," in *2021 IEEE 6th International Forum on Research and Technology for Society and Industry (RTSI)*, Naples, Italy, Sep. 2021, pp. 200–205, https://doi.org/10.1109/RTSI50628.2021.9597261.

[10] N. Thai, "Research on the operating voltage on the contact network of the subway system for the design of conductor rails – ROCS," in *Proceedings of the 2022 University Scientific Conference*, Ho Chi Minh City, Vietnam, 2022, pp. 83–89.

[11] S. Razmjou, "A Comprehensive DC Railway Traction System Simulator Based on MATLAB: Tabriz Line 2 Metro Project Case Study," *Journal of Operation and Automation in Power Engineering*, vol. 9, no. 2, pp. 144–159, Aug. 2021, https://doi.org/10.22098/joape.2021.8197.1569.

[12] F. Mao, Z. Mao, and K. Yu, "The Modeling and Simulation of DC Traction Power Supply Network for Urban Rail Transit Based on Simulink," *Journal of Physics: Conference Series*, vol. 1087, no. 4, Jun. 2018, Art. no. 042058, https://doi.org/10.1088/1742-6596/1087/4/042058.

[13] Z. Tian, N. Zhao, S. Hillmansen, S. Su, and C. Wen, "Traction Power Substation Load Analysis with Various Train Operating Styles and Substation Fault Modes," *Energies*, vol. 13, no. 11, Jan. 2020, Art. no. 2788, https://doi.org/10.3390/en13112788.

[14] H. Alnuman, D. Gladwin, and M. Foster, "Electrical Modelling of a DC Railway System with Multiple Trains," *Energies*, vol. 11, no. 11, Nov. 2018, Art. no. 3211, https://doi.org/10.3390/en11113211.

[15] E. Y. Abramov and V. I. Sopov, "Energy efficiency analysis of two-sided feed scheme of DC traction network with high asymmetry of feeders parameters," *IOP Conference Series: Earth and Environmental Science*, vol. 87, no. 3, Jul. 2017, Art. no. 032001, https://doi.org/10.1088/1755-1315/87/3/032001.

[16] F. Kiessling, R. Puschmann, A. Schmieder, and E. Schneider, *Contact Lines for Electric Railways: Planning, Design, Implementation, Maintenance*, 3rd ed. Erlangen: Publicis, 2018.

[17] P. Schmidt, *Energieversorgung elektrischer Bahnen*. Transpress, 1988.