An In-Depth Investigation of Innovative Electric Traction Power Supply Systems for Mass Rapid Transit

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ABSTRACT

This article discusses the outcomes of a study conducted to explore new power supply sources for subway trains. The power supply system for traction is an integral and inseparable component of subway rail infrastructure, encompassing both its management and operation. As a result, the specific choice of a power supply type has a lasting impact, either positive or negative, on the overall performance of a subway system. Consequently, researching power supply for traction presents a considerably more intricate challenge when compared to other railway transportation systems. In this study, the results obtained shed light on the pros and cons of utilizing the 25,000 V / 50 Hz system in comparison with the 1,500 V DC system, with a particular focus on traffic capacity and the efficiency of supplying traction power.

Keywords-MRT;metro; 1,500 V DC traction power; 25,000 V / 50 Hz traction power; high speed railway

I. INTRODUCTION

In today's urban rail transportation planning, subway systems are typically considered for cities with populations of two millions or more, and especially for those with populations exceeding four millions. Globally, the subway system is an integral part of the dynamic urban transportation network in major cities. It serves as the largest capacity transportation system to alleviate congestion during peak hours. The capacity of this system varies, ranging from low to medium, handling 20,000 passengers per hour per direction (p/h/d) to 40,000 p/h/d, medium to high capacity from 40,000 p/h/d to 64,000 p/h/d, and high to very high capacity from 64,000 p/h/d and higher [1-3, 33-34, 36]. The train capacity also varies, accommodating the needs of different routes and service frequencies. Trains are designed with capacities ranging from 4 cars for low capacity, 6 to 8 cars for high capacity, and 8 to 12 cars for very high capacity. Route requirements are matched with train capacities, which depend on train capacity and peak-hour service frequency, ranging from 5 minutes per train per direction (m/t/d) to 1.5 m/t/d, or as low as 72 sec per train per direction for automated systems at GoA4 standard [1-3, 33, 36]. Today, in the research and design of power supply for subway train traction, there is a strong correlation between route capacity and voltage, effectively becoming a "dual standard" with specific guidelines. For example, in systems with capacities below 40,000 p/h/d, a voltage of 750 V DC is typically used. For capacities ranging from 40,000 to 64,000 p/h/d, the standard voltage is 1,500 V DC, and for higher capacities, voltages of 3,000 V DC are employed in Brazil and Chile. There are exceptions, such as the new systems in India with a standardized voltage of 25,000 V AC at a frequency of 50 Hz [33, 36].

Throughout its history of formation and development, urban rail transportation, especially subways, has primarily relied on DC power systems, typically at higher voltage levels. The introduction of the 25,000 V / 50 Hz system in the southern region of France in 1953 marked a significant shift and is now predominantly used worldwide for long-distance and high-speed rail systems. However, in recent years, some countries with electrified railway systems have been exploring higher voltage power supply solutions to accommodate larger capacity transportation systems within urban areas [3-8].

In the early years of the 21st century, research on providing traction power for subway trains has undergone changes due to the increasing passenger capacity demands in densely populated countries. This shift necessitates that power supply solutions ensure fundamental factors such as supply capacity, reliability, and electrical safety for passengers and operational staff. Numerous methods have been studied worldwide to meet these criteria. However, the majority of these studies have primarily focused on enhancing the reliability of existing power sources, optimizing their efficiency, and improving the quality of power supply voltage [9-15]. Therefore, these studies may not align with the needs of countries that are planning subway systems and aiming for sustainable development, including Vietnam [36]. Hence, this paper explores various aspects of supplying 25,000 V AC at a frequency of 50 Hz (or 60 Hz) for subway trains in relation to DC systems with similar capacities.

Most studies in the design of electric traction power supply for subway trains involve comprehensive, efficient, and cost-effective simulations. In this study, Matlab R2017b/Railway Systems is the chosen software for simulating calculations in the power supply design, used in the form of writing scripts (code) according to a series of calculation formulas, suitable for the general application scenario presented in this article [3, 19-25, 31, 33].

II. TRACTION POWER SUPPLY SYSTEMS

A. *Traction Power Substation*

The subway is an electrical load with special power consumption characteristics due to its high-frequency service and is considered a type I electrical load. Therefore, supplying power to the subway requires more stringent requirements. The schematic diagram of the power supply system for the subway is generally described in Figure 1 and has the following technical features [3, 5-11]:

- High-voltage AC external power supply from 110 kV to 220 kV at 50Hz.
- High-voltage substation (BSS) for DC traction power supply and internal distribution network (DTS).
- In the 25,000 V / 50 Hz system traction power substation (TPS), with the core being traction transformer (TR): single-phase (I/I), star-star unbalanced, open delta/star unbalanced, open delta (V/V), star/delta-1, 11 (Y/D1, 11), Scott, LeBlanc, Modifine – Wood Bridge, Root – Delta [7-10].
- In the DC system TPS, consisting of AC/DC converters including: rectifier transformer and uncontrolled rectifier (TSR) [7-8]:
- Rectifier transformer (RTT): star, delta/delta, star; delta, star/star – delta; delta, star/six-phase with interphase transformer; delta, star/three-phase zigzag with interphase transformer; delta, star/two-phase zigzag with interphase transformer.
- Uncontrolled Rectifier (SR): three-phase bridge, parallel bridge, series bridge, double star six – phase half – wave with interphase transformer (reactor).
- Other basic components on the DC and AC traction sides such as DC Bus (BDC), negative (-), positive (+), AC Bus (BAC 25,000 V), power traction distribution cabinet and main circuit breakers and switches (CSB), contact line system (CLS), track (R), and return system (RS).
- Rated DC currents: 750 V DC, 1,500 V DC, and 3,000 V DC.
- The rated alternating current voltage is 25,000 V AC at a frequency of 50 Hz (25,000 V/ 50 Hz).
- All DC and AC operating voltages adhere to the EN 50163, UIC 600, and IEC 60850 standards.

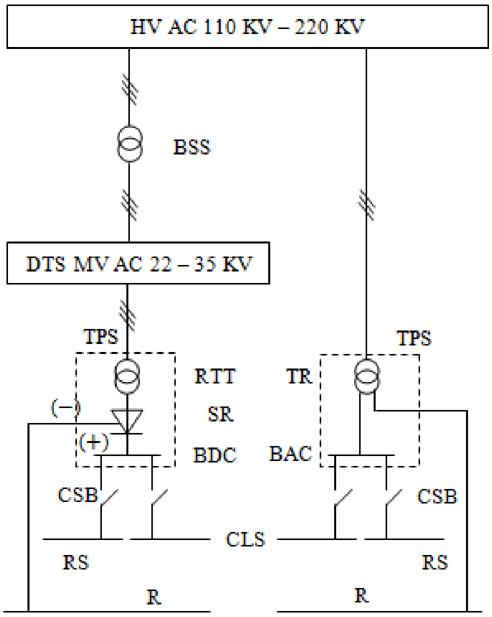

Fig. 1. General diagram of the subway power supply.

B. *Traction Power Distribution System*

1) *Direct Current Traction Power Distribution System*

The traction power distribution system in a basic subway system consists of the following [5-11]:

- Contact Line System: The system can use a third rail (3rdR) or an overhead contact line system (OCS). However, for a primarily 750 V DC system, the most common choice is the 3rdR contact network.
- Single-Feeding Power Supply: This network provides power from one direction only, as in Figure 2. The advantage of this network is its simplicity, easy installation of protective devices, and straightforward operation. However, its drawback is the significant voltage drop along the transmission line, limiting the loading capacity.

- Double-Feeding Power Supply: This network supplies power from two directions, as in Figure 3. Its advantages include reduced voltage drop, extended supply distance, higher loading capacity, and increased power delivery. However, the downside is that this network is more complex in structure, requires intricate protective device installation, and involves challenging maintenance.
- Section Post (SP): In low-voltage DC subway systems, there are typically no subsection posts (SSP), and only section posts (SP) exist. SP are simple junctions, vertical, diagonal, or horizontal, depending on the design calculations and operational contingencies. They are set up to handle potential incidents or for double – feeding power supply.

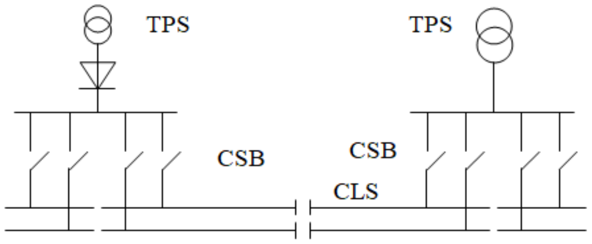

Fig. 2. A single – feeding power supply network.

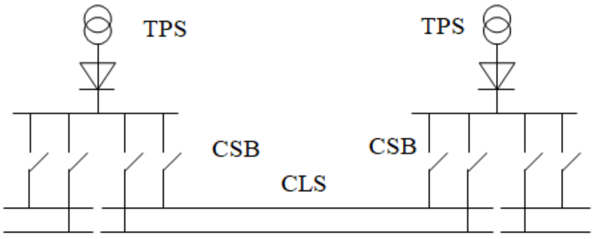

Fig. 3. A double – feeding power supply network.

2) *The AC 25,000 V / 50 Hz Distribution System*

The 25,000 V/ 50 Hz traction power distribution system through an overhead contact system and distribution structure consists off the following [5-7, 16-22, 31-32]:

- Direct Traction Distribution Network with Return Circuit Enhancement: Advantages: Simple, easy to operate, lower cost compared to other types. Disadvantages: Significant voltage drop along the transmission line, high electromagnetic field (EMF) and electromagnetic interference (EMI).
- Traction Distribution Network with Booter Transformer (BT): Advantages: Reduced leakage current, enhanced return current, reduced EMF and EMI [4-5]. Disadvantages: Increased impedance along the transmission line, flashovers due to contact arcing, reduced supply distance, increased installation and maintenance complexity.
- Traction Distribution Network with Auto Transformer (AT) [25-26]: Advantages: Increased transmission distance, reduced traction current on the section between two ATs, enhanced loading capacity, reduced leakage current, enhanced return current, reduced traction current on AT sections without running trains, reduced EMF and EMI impact. Disadvantages: Complex system, additional feeder cables (-25,000 V, F), complex switching and protection devices, increased installation cost.
- Sections Post (SP): Installed at the end of supply segments, with distances ranging from 40 km to 80 km depending on the load. Switches are always in the open position, and it becomes significantly more complex with AT systems.
- Subsection Post (SSP): Always in the closed position to maintain continuous power supply from the traction substation to the end of the supply segment during normal operation. Installation distance typically ranges from 20 km to 30 km.

III. SYSTEM DESIGN

A. *Load Calculation Method*

In the power supply design, the supplying capacity of a traction substation needs to meet the power consumption requirements of all trains within its supply range. The number of trains depends on the length of the supply range, train speed, and line capacity. In the dynamics of a train's motion, the electrical power consumption has a direct relationship with the speed of motion and the required traction force to achieve it, and an inverse relationship with mechanical efficiency and engine efficiency. Furthermore, during peak hours, the maximum power consumption depends on the number of trains operating within a supply range. Predicting power consumption in the design is carried out as follows:

Assuming that all other resistances due to railway terrain are disregarded, the maximum required power for trains in a journey is [2, 5, 10, 13, 22-27]:

$$P_t=\frac{(W_t+W_p)\cdot V}{\eta_c\cdot\eta_m\cdot 3.6}\cdot\left[\left(\frac{a}{g}\cdot\varepsilon\cdot 10^3\right)+\left(A+B\cdot V+C\cdot V^2\right)\right] \quad (1)$$

where W_t is the weight of the train, W_p is the total weight of the passengers, W is the total weight of train and passengers, η_c is the utility factor of mechanical transmission train, η_m is the utility factor of the traction motor, a is the acceleration of the train in every time step of the calculation, ε is the coefficient of rotating masses, g is the constant of gravity, V is the train velocity in every time step of the calculation, and A, B, C are the coefficients in the rolling resistance of W. J. Davis' formula.

The maximum instantaneous total power consumption under normal operating and the auxiliary power consumed on train (P_{aux}) are related by:

$$P_{TPSi\text{-}max} = \sum_{i=1}^{n}(P_t + P_{aux}) \quad (2)$$

The selected power in the design must ensure a margin for contingencies or unexpected load increases. Therefore, the rated design power for each substation must be greater than the calculated maximum power with a minimum reserve factor of 1.1. Voltage check is a crucial task in the design process: Let U_n be the rated voltage at the point where the contact line is supplied with a slight load increase or at rated current, and ΔU_x

be the voltage drop on the contact line at point x with the distribution of the load current on the section of train running. Then, the voltage supplied to the train at x is U_{tx}. If x moves to the end position of the source, then the maximum voltage drop is $\Delta U_{dc.max}$, and the minimum contact voltage is $U_{tx\text{-}min}$, determined as follows [2, 4, 10, 13, 20-29]:

$$I_{all} = \frac{60}{n} \cdot \frac{R_{TPS}}{v_{sc}} \cdot I_t \tag{3}$$

$$I_x = \frac{60}{n} \cdot \frac{L_x}{v_{sc}} \cdot I_t, \tag{4}$$

$$\Delta U_{dc.x} = \sum\nolimits_i I_{all} \cdot r_{cls} \cdot L_x \tag{5}$$

$$\Delta U_{dc.max} = \Delta U_{dc.x} + (I_{all} - I_x) \cdot r_{cls} \cdot (R_{TPS} - L_x) \tag{6}$$

$$U_{tx.min} = U_n - \Delta U_{dc.max} \tag{7}$$

where I_t is the traction current of the train, I_{all} is the total traction current of the trains on one RTPS segment, and $\Delta U_{dc.x}$ is the voltage drop at position x.

The selected traction substation's power rating must comply with the IEEE P1653.2, EN 50328, and IEC 60146-1 standards, and the operating voltage must adhere to the EN 50163, UIC 600, and IEC 60850 standards.

B. Load Parameters

The study was conducted on a hypothetical route with a length of 40 km in accordance with the planning in large cities and the current expansion construction trends in India, Korea, China, and the HCMC Metro of Vietnam (Line 1 and Line 2) [36]. Table I exhibits the system modeled parameters. n+1 is the number of traction AC/DC converters (transformers and rectifiers – TSR), 1 symbolizing the redundant converter, nTSR is the total number of AC/DC converters in a substation, DTPS is the distance between two traction power substations, and RTPS is the radius of a DTPS. The parameters related to the traffic capacity of the system are shown in Table II, whereas Table III shows the traction system assumptions.

IV. SIMULATION RESULT

A. Load Calculation

The train parameters were selected in order to meet the requirements of the described route, as outlined in Table II. The train capacities include both seated and standing passengers, with a maximum of 7 p/m^2. Four scenarios were analyzed, with passenger capacity increasing from 30,000 to 64,000 p/h/d. Each scenario offers three choices in the distribution of passenger flow and capacity corresponding to the peak-hour headway. The summary of the results of calculating the maximum capacity load per hour according to the route capacity requirements are described in Tables IV and V, where Pcal is the capacity calculated according to the traction force, Pn is the rated capacity according to the train's rated current, nTPS is the total number of TPS, u is the rated power per TSR or per TR, n/TPS is the number of TSR sets in a TPS, nTPS is the total TSR number used on the entire route, n/TR is the number of TR sets in a TPS, nTR shows the total TR used on the entire route, and Ptot is the total power traction demand on the entire route.

TABLE I. SYSTEM MODELING AND ASSUMPTIONS

Option	**1500 V DC**		**25 kV AC**	
1	D_{TPS} [km]	4	D_{TPS} [km]	20
	R_{TPS} [km]	2	R_{TPS} [km]	20
	n_{TPS} [km]	10	n_{TPS} [km]	2
	n_{TSR}	n+1	n_{TSR}	2.(1+1)
2	D_{TPS} [km]	4	D_{TPS} [km]	20
	R_{TPS} [km]	2.6	R_{TPS} [km]	10
	n_{TPS} [km]	10	n_{TPS} [km]	2
	n_{TSR}	n+1	n_{TSR}	2.(1+1)
3	D_{TPS} [km]	4	D_{TPS} [km]	40
	R_{TPS} [km]	4	R_{TPS} [km]	20
	n_{TPS} [km]	10	n_{TPS} [km]	1
	n_{TSR}	n+1	n_{TSR}	1+1

TABLE II. PARAMETERS OF TRAFFIC CAPACITY AND THE RESULT OF SELECTING THE PROVIDED CAPACITY [1-3, 4-6, 21-32]

Component	**Unit**	**Value**
Traffic capacity case 1, C_L^1	[p/h/d]	30,000
Traffic capacity case 2, C_L^2	[p/h/d]	40,000
Traffic capacity case 3, C_L^3	[p/h/d]	50,000
Traffic capacity case 4, C_L^4	[p/h/d]	64,000
Headway case 1...4 (n_1, n_2, n_3, n_4)	[m/t/d]	3.5; 3.0; 2.5; 2.0
Number of passengers per train, C_t^1	[p/t]	1,765
Number of passenger per train, C_t^2	[p/t]	2,000
Number of passengers per train, C_t^3	[p/t]	2,100
Number of passenger per train, C_t^4	[p/t]	2,150
Standard of passenger per square meter	[p/m^2]	5 – 7
Passenger per car (max)	[p/c]	300
Passenger weight, m_p	[kg/p]	65
Train weight, M_t	[t]	2.38 + 6.32
Train acceleration	[m/s^2]	0.95
Train velocity	[km/h]	50
Train configuration UIC	2’2’+ 6.Bo’Bo’+2’2’	
Resistance moving	[ton/kg]	
$R = 3,25+0,039 \cdot V+0,000659 \cdot V^2$		
Power of the train, P_t [kw]	3,900	
Train current, I [A]: 400·(6M)		
Auxilary current, I_{au} [A]: 25.3333·(6M) + 24·(2Mc)		

TABLE III. TRACTION SYSTEM ASSUMPTIONS [1-6, 21-32]

Component	**Value**
Running rail UIC 60	0.03 Ω/km/ rail, All four rails cross bonded: 0.0075 Ω/km
DC CuETp 150 + BzII 120	0.0156 Ω/km, Double track
AC CuMg AC 120 + Bz II 120	$0.391\angle 70^0$ (0.139 + j0.366) Ω/km, Double track
Un	1,500 V (DC)
Un	25,000 V (AC)

B. Discussion

1) Case 1

To meet the demand of 30,000 p/h/d with a supply capacity of 17 t/h/d and a train headway of 3.5 m/t/d, the total traction force required for accelerating to maximum speed is 363.92 N. The total weight is 365.07 tons. For a 1,500 V DC one-way system along the entire route with 10 traction substations, each requiring a power supply capacity of 12.2 MW (which is greater than the rated power of 11.88 MW), the total power required for the entire route is 122.01 MW. This would involve the use of 30 AC/DC converters.

TABLE IV. DESIGN RESULT, 1,500 V DC

Describe		Mass Rapid Transits: 1500 V DC											
		CASE 1			CASE 2			CASE 3			CASE 4		
Component	**Unit**	**Op 1**	**Op 2**	**Op 3**	**Op 1**	**Op 2**	**Op 3**	**Op 1**	**Op 2**	**Op 3**	**Op 1**	**Op 2**	**Op 3**
Line length	km	40	40	40	40	40	40	40	40	40	40	40	40
Station		40	40	40	40	40	40	40	40	40	40	40	40
headway	m/t/d	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0
C_L	p/h/d	30,000	30,000	30,000	40,000	40,000	40,000	50,000	50,000	50,000	64,000	64,000	64000
C_t	p/t	1,765	1,765	1,765	2,000	2,000	2,000	2,100	2,100	2,100	2,150	2,150	2,150
mp	Kg/p	55	55	55	55	55	55	55	55	55	55	55	55
Mt	Ton/t	268	268	268	268	268	268	268	268	268	268	268	268
M	Ton/t	365.07	365.07	365.07	378	378	378	383.5	383.5	383.5	386.25	386.25	386.25
Ft	N	363.92	363.92	363.92	376.81	376.81	376.81	382.29	382.29	382.29	385.05	385.05	385.05
D_{TPS}	km	4	4	4	4	4	4	4	4	4	4	4	4
R_{TPS}	km	2	2.6	4	2	2.6	4	2	2.6	4	2	2.6	4
Train/ R_{TPS}	n/d	0.762	1.0	1.52	0.89	1.16	1.78	1.067	1.387	2.133	1.333	1.733	2.667
Train/line	n/2d	30.47	30.47	30.47	35.6	35.6	35.6	42.667	42.667	42.667	53.333	53.333	53.333
Pcal/ R_{TPS}	MW	5.73	7.45	11.47	6.9	8.98	13.82	8.411	10.934	16.822	10.514	13.668	21.028
Pcal/TPS	MW	12.20	12.20	12.20	14.73	14.73	14.73	16.822	16.822	16.822	21.179	21.179	21.179
Pn/TPS	MW	11.88	11.88	11.88	13.86	13.86	13.86	16.640	16.640	16.640	20.800	20.800	20.800
n_{TPS}		10	10	10	10	10	10	10	10	10	10	10	10
u/TSR	MW	4.200	4.200	4.200	4.200	4.200	4.200	6.400	6.400	6.400	6.400	6.400	6.400
n/TSR		2+1	2+1	2+1	3+1	3+1	3+1	2+1	2+1	2+1	3+1	3+1	3+1
nTSR		30	30	30	40	40	40	30	30	30	40	40	40
Ptot	MW	122.01	122.01	122.01	147.39	147.39	147.39	168.22	168.22	168.22	211.79	211.79	211.79
Un	V	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Uo	V	1,665	1,665	1,665	1,665	1,665	1,665	1,665	1,665	1,665	1,665	1,665	1,665
Utx-min	V	1,408	1,.372	1,217	1.393	1.351	1170	1,372	1,321	1,104	1,339	1,268	1,001

TABLE V. DESIGN RESULT, 25,000 V / 50 HZ AC

Describe		Mass Rapid Transits: 2,5000 V AC/50HZ											
		CASE 1			CASE 2			CASE 3			CASE 4		
Component	**Unit**	**Op 1**	**Op 2**	**Op 3**	**Op 1**	**Op 2**	**Op 3**	**Op 1**	**Op 2**	**Op 3**	**Op 1**	**Op 2**	**Op 3**
Line length	km	40	40	40	40	40	40	40	40	40	40	40	40
Station		40	40	40	40	40	40	40	40	40	40	40	40
headway	m/t/d	3.5	3.5	3.5	3.0	3.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0
C_L	p/h/d	30,000	30,000	30,000	40,000	40,000	40,000	50,000	50,000	50,000	64,000	64,000	64,000
C_t	p/t	1,765	1,765	1,765	2,000	2,000	2,000	2,100	2,100	2,100	2,150	2,150	2,150
mp	Kg/p	55	55	55	55	55	55	55	55	55	55	55	55
Mt	Ton/t	268	268	268	268	268	268	268	268	268	268	268	268
M	Ton/t	365.07	365.07	365.07	378	378	378	383.5	383.5	383.5	386.25	386.25	386.25
Ft	N	363.92	363.92	363.92	376.81	376.81	376.81	382.29	382.29	382.29	385.05	385.05	385.05
D_{TPS}	km	20	40	20	20	40	20	20	40	20	20	40	20
R_{TPS}	km	10	20	30	10	20	30	10	20	30	10	20	30
Train/ R_{TPS}	n/d	3.80	7.62	11.43	4.44	8.88	13.33	5.33	10.66	16.00	6.67	13.33	20
Train/line	n/2d	30.47	30.47	30.47	35.56	35.56	35.56	42.67	42.67	42.67	53.33	53.33	53.33
Pcal/ R_{TPS}	MW	13.87	27.73	41.60	16.75	33.49	50.25	20.39	40.78	61.17	25.67	51.34	77.01
Pcal/TPS	MVA	61.01	122.02	61.01	73.69	147.39	73.69	84.11	168.22	84.11	105.89	211.79	105.89
Pn/TPS	MVA	59.43	118.8	59.43	69.33	138.67	69.33	83.2	166.40	83.20	104.00	208.00	104.00
n_{TPS}		2	1	2	2	1	2	2	1	2	2	1	2
u/TR	MVA	36.00	64.00	36.00	40.00	74.00	36.00	42.00	85.00	42.00	54.00	100.00	54.00
n/TR		2+1	2+1	2+1	2+1	2+1	2+1	2+1	2+1	2+1	2+1	2+1	2+1
nTR		6	3	6	6	3	6	6	3	6	6	3	6
Ptot	MVA	122.02	122.02	122.02	147.39	149.39	147.39	168.22	168.22	168.22	211.79	211.79	211.79
Uo	V	27,500	27,500	27,500	27,500	27,500	27,500	27,500	27,500	27,500	27,500	27,500	27,500
Un	V	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Utx – min	V	23,519	19,816	13,663	23,382	19,335	12,403	23,244	18,854	11,499	23,107	17,022	10,495
Umax – 1	V			27,500			27,500		27,500	27,500		27,500	27,500
Utx – min				16,163			14,903		21,354	13,949		19.522	12.995

In the case of different options for the basic current distribution structure from one direction, with a range of supply radii from 2 km (Op.1) to 4 km (Op.3), the minimum contact voltage at the farthest source end for the worst-case scenario (Op.3) is 1,217 V, which is greater than the 1,000 V DC standard as per EN 50163, UIC 600, and IEC 60850.

For the 25,000 V AC / 50 Hz system, there are three options for the power supply system structure: one traction substation or two traction substations. In the case of structure 1 (Op.1), the entire route is equipped with two traction substations, each with a power supply radius of 10 km. In this scenario, the calculated power for each substation is 61.01 MW (assuming neglecting losses from transformers and power factor). Therefore, the total power required is 122.02 MW. Assuming each traction transformer in the substation has a capacity of 36 MW, using two transformers per TPS and one spare transformer, a total of 6 traction transformers are required for the entire route.

When configuring the system with two traction substations along the entire route (Op.1), each with a 10 km supply radius, the contact voltage at the end of the segment is 23,519 V. If in Op.1, one substation experiences a fault, the segment with the largest power supply range is 30 km (corresponding to structure Op.3). In this scenario, the total number of trains in this segment increases to 11.43, resulting in an extremely high traction current. Consequently, maximum voltage drop occurs, leading to the minimum contact voltage at the end of the segment of 13,663 V, which is lower than the minimum voltage limit of 19,000 V. Even if the transformer tap is adjusted by 10% to 27,500 V (Umax - 1), the contact voltage at the end of the transmission line remains at 16,163 V, which is still lower than 19,000 V.

In the case of a centralized power source (Op.2) with one traction substation to meet the power consumption requirements, two transformers with a capacity of 64.00 MW each and one spare transformer are needed. In this scenario, the minimum contact voltage is 19,816 V at the end of the segment.

2) *Case 2*

The scenario was simulated with medium-level transportation demand of 40,000 p/h/d, designed with a supply capacity of 20 t/h/d and a train headway of 3.0 m/t/d. In this case, the total weight of a fully loaded train is 378 tons, and the maximum required traction force is 376.81 N.

For the 1,500 V DC system, during this phase, the rated power is 13.86 MW, and the power required for each traction substation is 14.74 MW. The structure involves modular units with each unit having a capacity of 4.2 MW installed in parallel with three units and one spare. The total power required for the entire route is 147.39 MW, and 40 AC/DC converters need to be installed. Similar to the previous scenario, the minimum contact voltage for the Op.1, Op.2, and Op.3 configurations is 1,393 V DC, 1,351 V DC, and 1,170 V DC, respectively. All these voltages are higher than the 1,000 V DC standard specified by EN 50163, UIC 600, and IEC 60850.

For the 25,000 V AC / 50 Hz system, with a configuration of two traction substations, the calculated power for each substation is 73.69 MW, which is higher than the rated power of 69.33 MW. Therefore, the total power required for the entire route is 147.39 MW. Assuming each traction transformer has a capacity of 40 MW, a total of 6 traction transformers are needed for this case. During normal operation or in the event of a fault, for the single substation configuration (Op.2), the minimum contact voltage is 19,335 V AC, and the power supply capacity for each transformer is 74.00 MW, with two transformers working in parallel and one spare. For the dual substation configuration along the route (Op.1), if operating normally, the minimum contact voltage at the end of the line (10 km) is 23,382 V AC. In the event of a fault at one substation (Op.3), with a power supply range of 30 km, the minimum contact voltage is 14,903 V, even when the transformer tap is increased by 10% (Umax - 1).

3) *Case 3*

In this scenario, the transportation demand is at a medium to high level of 50,000 passengers p/h/d, designed with a supply capacity of 24 t/h/d and a train headway of 2.5 m/t/d. In this case, the total weight of a fully loaded train is 383.5 tons, and the maximum required traction force is 382.29 N.

For the DC system, within the power supply range of a single traction substation for both directions, there are 4.2667 trains. Therefore, the total rated power of the load is 16.64 MW and the calculated power required for each traction substation is 16.822 MW/TPS. Since the power supply range of the traction substations is the same, the system is designed with 10 TPS, and the total power required for the entire route is 168.22 MW. In the case of configuration 3 (Op.3), with a distribution of 2.133 trains on a segment with a length of 4 km, the maximum voltage drop occurs at the end of the segment, resulting in a minimum contact voltage of 1,104 V. Therefore, with this power supply capacity and structure, the 1,500 V DC system can still meet the peak-hour traffic demand of 50,000 p/h/d, even in the event of an adjacent traction substation failure.

For the 25,000 V AC / 50 Hz system, the calculated power required for each traction substation with Op.1 and Op.3 configurations is 84.11 MW, comparable to the rated power of 83.2 MW. On the route designed with two traction substations, the minimum number of transformers designed is 2 per substation in parallel with one spare, resulting in a total of 6 transformers, each with a minimum power rating of 42 MW per transformer for both Op.1 and Op.3 cases. In the case of the Op.2 configuration on the route designed with a single traction substation, the total required power capacity is 168.22 MW. Therefore, to meet this capacity, two transformers, each with a capacity of 85 MW, are used in the substation, with two transformers operating in load-sharing and one spare. Regarding the operating voltage, with the Op.1 configuration supplying power on both directions of a traction substation over a 10 km range, with 5.33 trains appearing on each direction, the minimum contact voltage at the end of the segment is 23,244 V AC. However, with this configuration, in the event of a traction substation failure, the segment with the largest power supply range is 30 km, with the presence of 16 trains on the segment. Similar to the previous cases, an extremely large voltage drop occurs, resulting in an extremely low contact voltage of 13,949 V, even after adjusting the transformer tap by 10%. For Op.2, in the case of normal operation, the minimum contact voltage at the end of the segment is 18,854 V AC, which is lower than the minimum standard allowed. When increasing the transformer tap by 10%, the contact voltage at the end of the segment is 21,354 V, which complies with the EN 50163, UIC 600, and IEC 60850 standards.

4) Case 4

This scenario corresponds to a high capacity level, with a transportation demand of 64,000 p/h/d, designed with a line capacity of 30 t/h/d. The total weight of a fully loaded train is 386.25 tons and the maximum required traction force is 385.05 N.

In Case 4, with a service headway of 2.0 m/t/d, a total route length of 40 km, and a travel speed of 45 km/h, the average density of load distribution on the route is 1.066 trains per km. Since the stations are evenly spaced, the power capacity is the same for all stations, calculated at 21.179 MW (as per the calculation) and 20.80 MW (rated capacity). Each set of power equipment has a capacity of 6.4 MW, and each station is equipped with 4 sets. The operating voltage for each configuration from Op.1 to Op.3 is 1,339 V DC, 1,268 V DC, and 1,001 V DC.

For the 25,000 V AC system, with a calculated power capacity of 105.89 MW per traction substation (comparable to the rated capacity of 104.00 MW), each traction substation requires a minimum of two operating transformers and one spare, with each transformer having a capacity of 54.00 MW. In configuration 2 (Op.2), only one substation is installed on the route, so the minimum power capacity of the substation must be greater than the rated capacity, and each transformer has a capacity of 100 MW. The minimum contact voltage in configuration 1 (Op.1) is 23,107 V AC, and in Op.2, it is 19,522 V, with the transformer tap adjusted by 10%. For configuration Op.3, the contact voltage is 12,995 V AC after adjusting the transformer tap by 10%. Overall, the cases of load are classified in ascending order to facilitate the assessment of load increase and voltage drop along a constant length of the power distribution structure. This demonstrates that, within the typical power supply range of a traction substation for 1,500 V DC underground railways, which is around 4 km with traffic loads ranging from 30,000 to 64,000 p/h/d, the system can adequately meet the load requirements and operational voltage conditions when supplied from one direction. However, the supply capacity for traffic can increase if an optimized power supply structure scheme is employed.

Traditionally, the 25,000 V AC / 50 Hz (or 60 Hz) systems are mainly designed for local, long-distance passenger and freight rail systems, as well as high-speed railways. For these types of railways, although they use high-powered trains, the train service frequency is low, and the speed is high. As a result, the distribution of current per kilometer of track is low, leading to a minimal voltage drop at the end of the line. Therefore, the minimum contact voltage limit is not typically violated in these systems. However, for subway systems, due to their high train service frequency, the current distribution per kilometer of track is high. As the distance between traction substations increases, the voltage drop at the end of the line increases, resulting in a lower contact voltage as seen in configurations Op.2 and Op.3. Furthermore, in the case of an increased load, the 25,000 V AC / 50 Hz system cannot change the power supply structure from one direction to two directions as in direct current systems. The rated power of traction transformers increases when the capacity of the line load increases. Using transformers with capacities greater than 40 MVA significantly increases costs compared to transformers with capacities less than 40 MVA. With a traffic capacity of 64,000 p/h/d, when the supply radius increases, the minimum required capacity of traction transformer substations becomes excessively large, even exceeding those of high-speed railway substations. Overloading the 25,000 V AC system is an unacceptable scenario for underground trains since the operating conditions of such transformers should not exceed a 50% overload for 15 min and a 100% overload for 5 min (according to EN 50329, IEC 60076-5, 60076-7, 60076-10 standards). Additionally, using high voltage requires larger safety clearances, more expensive high-voltage equipment, more complex maintenance and operation, and higher infrastructure construction costs. Specifically, there are currently no voltage operation standards and design guidelines for using 25,000 V AC / 50 Hz in subway systems. However, despite these disadvantages, the 25,000 V AC system also has notable advantages, particularly when it comes to requiring fewer traction substation stations than the 1,500 V DC system. This is especially advantageous for longer lines with an average distance of around 40 km per traction power substation when the line's capacity is below 50,000 p/h/d, and greater capacity with more complex system structures.

V. CONCLUSION

The current article presents the results of a study on new power supply sources for subway trains. The research examines various contrasting scenarios of load cases, ranging from incremental power demand to the maximum corresponding to the 1,500 V DC operating voltage. It also explores multiple options for power distribution structures, aiming to highlight the advantages and disadvantages of power source choices.

The research results indicate that the power consumption of the load and supply requirements in the 25,000 V AC / 50 Hz system are constrained by factors such as line length, segment length, and transformer capacity.

Through the power aspect of the research findings, it becomes evident that the selection of a sustainable power source is critical for making informed choices. Choosing the wrong power supply system can have negative implications to the urban railway systems. Other issues resulting from the influence of the 25,000 V AC / 50 Hz system will be addressed in future studies.

Finally, the results in this study are a reliable basis for comparing investment costs for 1,500V DC or 25,000 V AC systems throughout their life cycle.

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