The Design Method of Traction Power Supplies in Integrated Metro Systems

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ABSTRACT

Integrated subway systems have emerged as a new trend that provides the highest quality service at the lowest investment cost by combining the advantages of the two largest passenger transport capabilities during peak hours. Under the integrated model, designing the traction power supply is much more complex than for other independent systems. This article presents the results of a study on the method of calculating the design load of the power supply for the transport operation of the system. Matlab R2017b/Railway Systems is a reliable software for simulating and analyzing some necessary data, and the research results show the feasibility of the method when applied to the case of asynchronous load on the system. The results meet the power supply design standards according to IEEE P1653.2, EN 50328, and IEC 60146-1 overload allowances for class VI, and voltage standards according to EN 50163, UIC 600, and IEC 60850.

Keywords-subway train; integrated subway system; urban integrated railway; traction substation

I. INTRODUCTION

The integrated subway model - MRC is a combination of subway trains (MRT) and suburban trains (CR). This combination model allows the operation with a very large transport capacity during peak hours in order to meet the demand for travel between the suburbs and the city center, which each type alone cannot meet, and to return to the separate normal operating state of each type during off-peak hours with the lowest investment cost and the highest service quality. This method allows for increasing the transport capacity and service frequency of the subway line without the need to increase the number of purchased trains operating on the line. On the other hand, the suburban train, when running on the line, will operate like a subway train. The diagram of the integrated train operation is described in Figure 1 of [1], in which A to E are the terminal stations of the subway line, B to E (or B to A but stops at any station) the terminal stations of the suburban railway, and B to A is the integrated peak-hour suburban railway station.

Over the past few years, many studies have emphasized the advantages of having a subway system that is integrated [2-6]. To guarantee that the system operates in a manner that is flexible, efficient, dependable, and energy-saving, it must have a robust power supply system that can support maximum transportation capacity during peak hours. Despite this, the majority of research studies have concentrated on planning, predicting, and handling transportation capacity and energy conservation while assessing the advantages it provides to the overall development of smart cities in the current integrated subway context [7-11]. Some recent studies have been conducted on the method of designing the power supply for electric subway trains [12-20] and the study of operating voltage in a pure system [19]. This article presents the results of the research on calculating the design of traction power supply for the integrated system. In the design of the power supply for traction, to ensure continuous, flexible, reliable, safe, and efficient system operation, the traction power station capacity must meet two evaluation criteria: power supply capacity and minimum contact voltage allowed in normal operating conditions and emergencies.

The majority of the research on creating power systems for subway trains uses computer simulations that are comprehensive, effective, and affordable. In this particular study, the software chosen for simulating and calculating a power supply that meets the global standards is Matlab R2017b/Railway Systems.

II. METHODOLOGY

A. Calculating the Power of the Traction Substation

There are many methods used to calculate the design load of the electric traction power supply for a subway or suburban railway system [12-20]. However, these methods only allow separate calculations for each system. For integrated systems that combine two systems with different capacities on the same power supply system, this difference, which arises from the characteristics of the train, is an important issue in load calculation. Since the transport capacity of subway and suburban trains is different, the current used is also different. Correspondingly, the acceleration and operating speed are different, so the mechanical resistance (R_r) and acceleration resistance (R_a) are also different. As a result, the maximum instantaneous traction force performed on each cycle of each train trip between the two stations is different. From all these differences, an asynchronous load is created over the range of the power supply of a traction substation. Therefore, calculating this complex asynchronous load needs to meet the demand for the highest power usage during peak hours.

The components of train motion resistance (R_r), acceleration resistance (R_a), curve resistance (Rc), gradient resistance (R_g), and tunnel resistance (R_t) can appear in one cycle of the train motion starting at station j within the power supply range of a traction substation i.

$$R_{rx,y} = A + Bv + Cv^2 \quad (1)$$

$$R_{gi,j} = \pm G/1000 \quad (2)$$

$$R_{ti,j} = \frac{f_t \cdot v^2}{W} \quad (3)$$

$$\begin{cases} R_{ci,j} = \frac{650}{r-55}, & r < 300 \\ R_{ci,j} = \frac{500}{r-30}, & r \geq 300 \end{cases} \quad (4)$$

$$R_{a.x,y.i,j} = \frac{a\xi}{g} \quad (5)$$

The maximum resistance is:

$$\begin{cases} \sum R_{i,j} = R_{ci,j} + R_{gi,j} + R_{ti,j} \\ R_{max.i,j} \leq \sum R_{i,j} < R_a + R_r \end{cases} \quad (6)$$

Let M_x and M_y be the total weight of the subway train x and the suburban train y at full load with maximum carrying capacity. The maximum instantaneous traction force of train x and y in each direction, within the supply range of a traction power station i and traveling from station j in the direction of k and towards h, can be calculated:

$$F_{ti,j\text{-}kx,max} = M_x \cdot \left(R_{a,x} + R_{r,x} + \sum R_{max,j\text{-}kx}\right) \quad (7)$$

$$\sum R_{max,j\text{-}kx} = R_{c,j\text{-}kx} + R_{g,j\text{-}kx} + R_{t,j\text{-}kx} \quad (8)$$

$$F_{ti,j\text{-}hx,max} = M_x \cdot \left(R_{a,x} + R_{r,x} + \sum R_{max,j\text{-}hx}\right) \quad (9)$$

$$\sum R_{max,j\text{-}hx} = R_{c,j\text{-}hx} + R_{g,j\text{-}hx} + R_{t,j\text{-}hx} \quad (10)$$

$$F_{ti,j\text{-}ky,max} = M_y \cdot \left(R_{a,y} + R_{r,y} + \sum R_{max,j\text{-}ky}\right) \quad (11)$$

$$\sum R_{max,j\text{-}ky} = R_{c,j\text{-}ky} + R_{g,j\text{-}ky} + R_{t,j\text{-}ky} \quad (12)$$

$$F_{ti,j\text{-}hy,max} = M_y \cdot \left(R_{a,y} + R_{r,y} + \sum R_{max,j\text{-}hy}\right) \quad (13)$$

$$\sum R_{max,j\text{-}hy} = R_{c,j\text{-}hy} + R_{g,j\text{-}hy} + R_{t,j\text{-}hy} \quad (14)$$

The maximum traction force under normal conditions is:

$$\sum_{i=1}^{1} F_{ti,j,\,(na)max} = \sum_{na.\,p_l \in i,j} p_{l,max} \cdot F_{ti,j,(na)max} \quad (15)$$

where:

$$\begin{cases} \sum_{na.\,p_l \in i,j} p_{l,max} = \frac{60}{c_{l,max}} \cdot \frac{D_{TPSi}}{v_{sc}} \cdot 2 \\ 1,25 \leq c_{l,max} < c_{l,MRT},\ c_{l,max} = \frac{C_{p,max}}{C_{t,max}} \\ F_{ti,j,(na)max} \in kx, hx, ky, hy \end{cases} \quad (16)$$

When an error (er) occurs:

$$\sum_{i=1}^{i+\frac{1}{2}} F_{ti,j,\,(er),max} = \sum_{er.p_l \in i,j} p_{l,max} \cdot F_{ti,j,(er)max} \quad (17)$$

where:

$$\begin{cases} \sum_{er.\,p_l \in i,j} p_{l,max} = \frac{60}{c_{l,max}} \cdot \frac{2}{v_{sc}} \cdot \left[D_{TPSi} + \frac{D_{TPS(i+1)}}{2}\right] \\ 1,25 \leq c_{l,max} < c_{l,MRT},\ c_{l,max} = \frac{C_{p,max}}{C_{t,max}} \\ F_{ti,j,(na)max} \in kx, hx, ky, hy \end{cases} \quad (18)$$

The maximum instantaneous power demand within an hour is described by:

$$P_{ti,j(na)max} = \sum_{i=1}^{p_{l(na),max}} F_{ti,j,\,(na)max} \cdot \frac{v}{3{,}6 \cdot \eta_{mc} \cdot \eta_{mt}} \quad (19)$$

$$P_{ti,j(er)max} = \sum_{i=1}^{p_{l(er),max}} F_{ti,j,\,(er)max} \cdot \frac{v}{3{,}6 \cdot \eta_{mc} \cdot \eta_{mt}} \quad (20)$$

where η_{mc} and η_{mt} are the mechanical and engine efficiency respectively:

$$\begin{cases} \eta_{mc,min} < \eta_{mc} \leq \eta_{mc,max} \\ \eta_{mt,min} < \eta_{mt} \leq \eta_{mt,max} \\ v_{sc} < v \leq v_{peak} \end{cases} \quad (21)$$

The auxiliary power consumption is:

$$P_{[x,y],i(na)aux} = \sum_{na.\,p_l \in i} p_{l,max} \begin{pmatrix} n_{[x,y]} \cdot p_{d,[x,y]} \\ + m_{[x,y]} \cdot p_{c,[x,y]} \end{pmatrix} \quad (22)$$

$$P_{[x,y],i(er)aux} = \sum_{er.\,p_l \in i} p_{l,max} \begin{pmatrix} n_{[x,y]} \cdot p_{d,[x,y]} \\ + m_{[x,y]} \cdot p_{c,[x,y]} \end{pmatrix} \quad (23)$$

The maximum instantaneous total power requirement within an hour is defined as:

$$P_{TPSi(na)max} = P_{ti,j(na)max} + P_{[x,y],i(na)aux} \quad (23)$$

$$P_{TPSi(er)max} = P_{ti,j(er)max} + P_{[x,y],i(er)aux} \quad (24)$$

If the system has regenerative braking, the percentage of energy recovered η_{re} is:

$$P_{TPSi(re,\,na)max} = P_{TPSi(na)max}\left(1 - \eta_{re}\right) \quad (25)$$

$$P_{TPSi(re,\,er)max} = P_{TPSi(er)max}\left(1 - \eta_{re}\right) \quad (26)$$

with criterion:

$$\begin{cases} \eta_{re,na.\,min} < \eta_{re[x,y]} \le \eta_{re,na,.max} \\ \eta_{re,er.\,min} < \eta_{re[x,y]} \le \eta_{re,er.max} \end{cases} \quad (27)$$

The power selection for the traction substation is:

$$P_{TPSi(er,na)max} \le P_{TPSi(na),\,min} \quad (28)$$

$$P_{TPSi(re,\,er)max} \le P_{TPSi(re),\,min} \quad (29)$$

$$P_{TPSi(re),min} < P_{TPSi} \le P_{TPSi(na),\,min} \quad (30)$$

Therefore, the selected power for the traction substation according to (28)-(30) must comply with IEEE P1653.2, EN 50328, and IEC 60146-1 standards.

B. *Operating Voltage*

Let $U_{dc\text{-}o}$, U_{fdc}, and $U_{tx:xi,yi}$ be the operating voltage of the unloaded rectifier, the supply voltage, and the contact voltage, respectively:

$$I_{i(na)max} = \sum_{1}^{c_{l,max}} I_{x,y\ (i)\in \sum_{na.\ p_l \in i,j} p_{l,max}} \quad (31)$$

$$I_{i(er)max} = \sum_{1}^{c_{l,max}} I_{x,y\ (i)\in \sum_{er.\ p_l \in i,j} p_{l,max}} \quad (32)$$

$$U_{fdc,(na,\,er)} = U_{dc\text{-}o} - I_{i(na,\,er)max} \cdot \sum R_{TPSi,\ cf} \quad (33)$$

$$\sum \Delta U_{dc:j,\,j+xmax} = I_{i(na,er),Lx} \cdot r_{cls} \cdot L_x + I_{i(na,er),x} \cdot r_{cls} \cdot x_{max} \quad (34)$$

$$U_{tx(na,\,er),min} = U_{fdc,(na,\,er)} - \sum \Delta U_{dc:j,\,j+xmax} \quad (35)$$

The minimum contact voltage at the end of the power supply section of a traction substation operating in normal or fault conditions must satisfy the operating voltage requirements of the EN 50163, UIC 600, and IEC 60850 standards, as specified in (35).

III. SYSTEM DESIGN

A. *Load Parameters*

The route profile from substation 3 to substation 4 can be seen in Table I. TPSi is the i^{th} traction substation, STj is the j^{th} passenger station, G‰ is the lope of the railway, C is the curve radius, Rt is the coefficient of tunnel resistance for smooth plane double track, and SP is the end of power supply section. The load parameters are exhibited in Table II and the traction parameters in Table III [1].

TABLE I. PROFILE OF THE ROUTE FROM TRACTION SUBSTATION NO. 3 TO NO. 4 ALONG THE LINE

Km	TPSi	STj	G‰	C	Rt
10.0	SP	11			
11.00		12			
11.50			+35	650	
12.00		13			
12.40	3				
13.20		14			
13.70			+5	500	
14.00	SP				
14.40		15			
15.40		16	-5		17.14
15.80			-20		17.14
16.00	4				17.14
16.40		17			17.14
17.40		18			17.14

TABLE II. TRAIN LOAD PARAMETERS

Symbol	Specifications	Description
$C_{p1;2}$	45.000; 54.000	Person/hour/direction
n_x, n_y	2; 2	Control car
m_x, m_y	6; 5	locomotive unit
$m_{d,x;y}$	40 tons; 42 tons	Control car
$m_{c,x;y}$	38 tons; 41 tons	Locomotive unit
$S_{d,x}$	3.2×22 m²	Floor area of a passenger car
$S_{c,x}$	3.2×23 m²	Passenger area
$S_{d,y}$	3.27×25 m²	Floor area of a passenger car
$S_{c,y}$	3.27×26 m²	Passenger area
$f_{s.d,x;y}$	0.45%; 0.42%	Occupancy rate
$f_{s.c,x;y}$	0.55%; 0.45%	Occupancy rate
$f_{d,x}$	38 seats	Cabin seat
$f_{c,x}$	44 seats	Passenger seat
$f_{d,y}$	32 seats	Cabin seat
$f_{c,y}$	42 seats	Passenger seat
m_p	55 kg	Weight/passenger

TABLE III. TRAIN TRACTION PARAMETERS

Symbol	Metric	Value
$C_{L.p1}$	[p/h/d]	45,000
$C_{L.p2}$	[p/h/d]	54,000
$a_{x,max}/\beta_{x,max}$	[m/s²]	0.9/1.0
$a_{y,max}/\beta_{y,max}$	[m/s²]	0.85/1.0
R_x, R_y	[kg/tấn]	
$R_x = 3.25 + 0.039 \cdot V + 0.000659 \cdot V^2$		
$R_y = 2.45 + 0.044 \cdot V + 0.000374 \cdot V^2$		
v_{sc}, v_{max}	[km/h]	45/60
Train load Ix [A]: 400·(4M)+200·(2M)+200·(2Mc)		
Train load [A]: 400·(4M)+200·(1M)+200·(2Mc)		
Support load Iaux [A]: 25.3333·(6M)+24·(2Mc)		
Support load Iauy [A]: 26.6667·(5M)+24·(2Mc)		

B. *Design of the Calculation Process*

The process of calculating the design of a pullable electrical supply is described as an algorithmic flowchart in Figure 1.

IV. RESULTS AND DISCUSSION

A. *The Result of Selecting the Power Capacity for the Traction Substation*

1) *Case 1*

The calculated power capacity for traction substation No. 3 in case 1 is presented in Table IV.

In summary, the maximum calculated power required for the traction of both normal operation and contingency situations meets the actual power consumption demand of the selected train load. Therefore, it satisfies the design calculation requirements. The selected power capacity of the traction substation must also meet the overload conditions in both normal and contingency situations. The chosen power per unit converter is 3,2000MW, and the traction substation power is 6,4000MW, which is less than the actual power consumption demand of 6,5113MW, but greater than the demand in cases of regeneration when braking normally and in contingency situations, which are 3,9068MW and 5,8602MW, respectively.

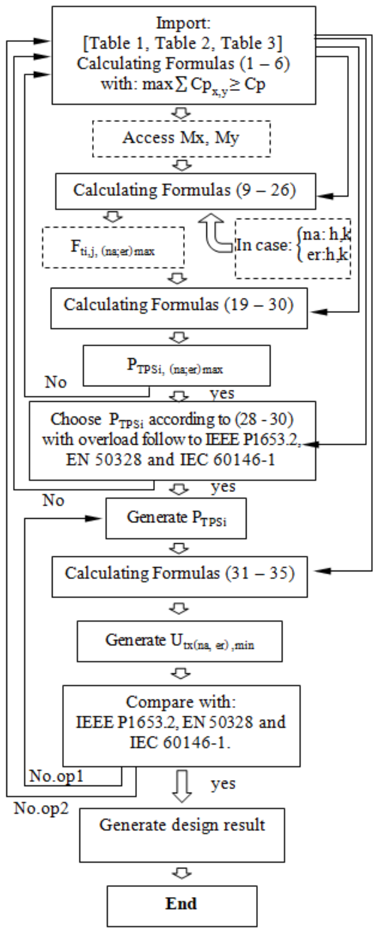

Fig. 1. Flowchart of the load calculation process.

TABLE IV. THE CALCULATED POWER CAPACITY FOR TRACTION SUBSTATION NO. 3 IN CASE 1

Component	Phase 1	Ph 2
n	3.0000	2.5000
Fmax [kN]	244.4978	244.4978
Pmax.na [MW]	7.9319	9.5183
Pmax.er [MW]	11.8989	14.2775
Pre.na [MVA]	4.7592	5.7110
Pre.er [MVA]	7.1387	8.5665
Pload.na [MW]	6.5113	7.8136
Pload.er [MW]	9.7670	11.7203
Pldre.na [MW]	3.9068	4.6881
Pldre.er [MW]	5.8602	7.0322
prec [MW/dv]	3.2000	3.2000
nprec [dv]	2+1	3+1
Ptps [MW]	6.4000	9.600
Pol.na(2h) [MW]	9.6000	14.4000
Pol.er(2h) [MW]	14.4000	14.4000

The power supply capacity of the traction substation with the ability to withstand overload for two continuous hours according to the IEEE P1653.2, EN 50328, and IEC 60146-1 standards, is 9,6000MW, which is greater than the actual consumption demand of 6,5113MW and the theoretical calculation of 7,9319MW for normal operation. The ability to withstand overload for contingency situations is 14,4000MW (all three converters working together), which is greater than the actual consumption demand of 9,7670MW and the theoretical calculation of 11,8979MW.

In phase 2, under normal circumstances, the station operates with three power supply units providing 9,6000MW, which is greater than the maximum calculated power requirement of 9,5183MW, the regeneration requirement under contingency situations of 8,5665MW, and the actual power consumption demand of 7,0322MW. If there is no regeneration, the overload capacity is 14,4000MW, which is greater than the maximum calculated power requirement of 14,2775MW and the actual power consumption demand of 11,7203MW. Therefore, the analysis of the results shows that the selected power capacity is suitable for the required load demand.

2) *Case 2*

In the case of an incident, traction substation number 3 must also supply power to an additional segment from traction substation number 4. The calculated power capacity for traction substation number 3 in case 2 is shown in Table V.

TABLE V. THE CALCULATED POWER CAPACITY FOR TRACTION SUBSTATION NO. 3 IN CASE 2

Component	Phase 1	Phase 2
nCR	4.5000	3.0000
nInter	3.0000	2.5000
FmaxCR [kN]	205.6862	205.6862
FmaxInter [kN]	244.4978	244.4978
Pmax.na [MW]	4.5590	6.8385
Pmax.er [MW]	9.2539	12.6911
Pre.na [MVA]	3.1913	4.7869
Pre.er [MVA]	6.4777	8.8838
Pload.na [MW]	3.9758	5.9637
Pload.er [MW]	7.5965	10.4181
Pldre.na [MW]	2.7831	4.1746
Pldre.er [MW]	5.3176	7.2927
prec [MW/dv]	3.2000	3.2000
nprec [dv]	2+1	2+1
Ptps [MW]	6.4000	9.600
Pol.na(2h) [MW]	9.6000	14.4000
Pol.er(2h) [MW]	14.4000	14.4000

In this case, the selected power capacity for the station must meet two different loads. The capacity of each rectifier unit is 3.2000MW, and the station is designed with a (2+1) configuration for each load phase. In phase 1, the station supplies a capacity of 6.4000MW, which is greater than the normal maximum load calculation (4.5590MW) and the contingency load in case of regeneration inhibition (5.3176MW), but smaller than the normal maximum load calculation without any contingency (9.2539MW). However, the station's ability to withstand 150% overload for two consecutive peak hours is 9.6000MW, which is higher than the actual consumption load (7.5965MW) and even the maximum calculated contingency load without regeneration inhibition (9.2539MW), meeting the standards' requirements.

In phase 2, under normal operating conditions, the station provides the rated power of 6.4000MW, which is lower than the maximum calculated load (6.8385MW), but the ability to withstand overload is up to 9.6000MW in the event of regeneration inhibition (8.8838MW and 7.2927MW), but cannot handle contingencies without regeneration inhibition. Therefore, in this case, the station must operate with three rectifier units simultaneously with a total capacity of 9.6000MW, with the ability to handle overload up to 14.4000MW, which is higher than the actual consumption capacity of 10.4181MW and the maximum calculated capacity of 12.6911MW. Thus, the analysis results show that the selected power capacity is suitable for the load requirements.

The calculated and selected power capacity for the traction substation in both cases 1 and 2 are based on the comprehensive calculation method for the integrated subway train load. This method effectively meets the load requirements and ensures good performance for 150% overload capability for two consecutive hours. Therefore, there is no need to consider overload cases of 200%, 300%, and 450%, as per the criteria for evaluating the design of traction substation power capacity specified by IEEE P1653.2, EN 50328, and IEC 60146-1.

B. Operating Voltage

Checking the operating voltage is the final step in designing the power supply for this integrated subway electrical load.

In phase 1, the unloaded rectified voltage is 1.656V for two parallel rectifiers in normal operation and three rectifiers in the event of a failure, as shown in Figure 2.

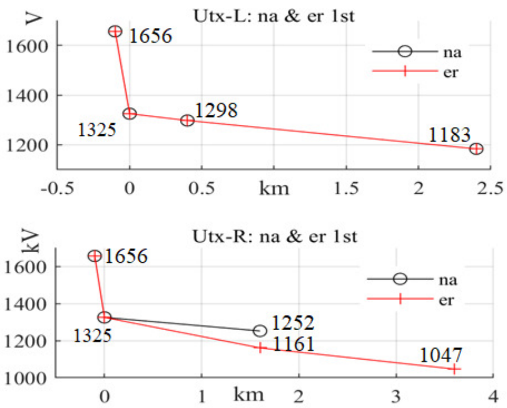

Fig. 2. Operating voltage in phase 1.

On the left segment, the supplied voltage at the supply station is 1.325V and the contact voltage at the furthest end of the left segment is 1.183V. On the right segment, the contact voltage at the end of the segment is 1.252V in normal operation and 1.161V in case of a failure, and the contact voltage at the extended segment is 1.047V. Therefore, in phase 1, the smallest contact voltage at the end of the extended segment in case of a failure is 1.047V, which is higher than the minimum allowable limit of 1.000V.

In phase 2, in normal operation with three parallel rectifiers, the no-load voltage is 1.656V, as shown in Figure 3. In normal operation, the supply voltage at the supply station for both sections is 1.391V, the minimum contact voltage on the left section is 1.221V, and the minimum contact voltage on the right section is 1.266V, which is greater than the minimum allowed voltage of 1.000V. In the event of a fault, the supply voltage is 1.259V on both left and right sections, the minimum contact voltage on the left section is 1.089V, and the minimum on the extended right section is 957.5V. Thus, although the station using 3 rectifiers, it exceeds the allowable overload power of 150% (14.4MW) according to the standard, violating the voltage standard (957.5V < 1.000V). Therefore, the station's capacity must be increased by using 4 parallel-connected rectifiers, at which time the supply voltage on both sections is 1.358V, the minimum contact voltage on the left section is 1.188V, and the minimum contact voltage on the extended right section is 1.057V, which is greater than the minimum allowable voltage of 1.000V according to EN 50163, UIC 600, and IEC 60850 standards. Thus, increasing the power supply capacity at the traction substation can meet the demand of the load consumption, reduce voltage drop, and increase the contact voltage to satisfy the selection condition 1 (No.op1), without considering the selection condition 2 (No.op2) in the design calculation process.

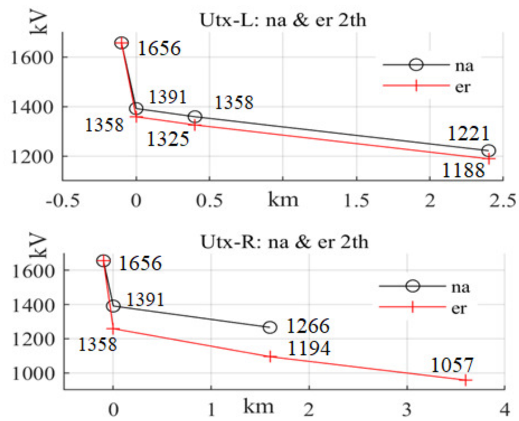

Fig. 3. Operating voltage in phase 2.

V. CONCLUSION

The current paper proposes a calculative method for the power design of a traction substation based on the maximum instantaneous traction force calculation under the integrated subway railway model. The method was designed and simulated on Matlab R2017b/Railway Systems, and its reliability was demonstrated through various cases of loads for maximum power during peak hours. The method also ensures transparency and logic when calculating data in a sequence with filtering and cross-referencing for backup situations to avoid power waste. The calculated power is higher than the load demand from 14.67% to 21.81%, allowing the selection of a substation power that meets the standards for the redundancy factor and the allowed range of low voltage overload operation.

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