Temporal Fluctuated Features of Metro Traction Load Current in DC Railway

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ABSTRACT
24-hour traction current based on Wuhan Metro Line 6 are reported. The fluctuation features, which corresponding to the interval of vehicle operation, indicate that there are four types of inrush current periodically appearing throughout the all-day waveforms. The first type consists of two positive sharp waves. The second type is saddle shaped, and consists of two positive peaks and an anti-peak. The third type consists of two double peaks followed by a sharp peak about 1 minute later. The fourth type consists of two hump shaped waveforms. The whole operation time can be divided into the peak and off-peak hours according to these repetitive segments. The interval of any two adjacent vehicles is 9 minutes and 11 minutes, respectively, in peak and off-peak hours. The distribution and the positive average value of feeder current per hour from 6:00-24:00 are counted and analyzed. Results show that the current distribution in off-peak hours is more concentrated in a narrower range than that in peak hours. The differences in averages between various 15-minute periods in an hour can be as high as tens of amperes, due to the occurrence time of repetitive segments. The rail potential has relatively consistent variation with feeder currents, but it matched best with the sum of up-line and down-line in a same section instead of one of the two lines.

INDEX TERMS
Intelligent transportation systems, traction power supplies, railway engineering, system testing.

I. INTRODUCTION
In DC railway systems, the traction power substation (TPS) supplies energy for vehicles on its both sides. Different voltage levels from 500V to 3000V are used as power supply for vehicle operation [1]. In Wuhan Metro Systems, Line 6 is the first metro line supplied by 1500V DC power, whereas the remaining others are supplied by 750V DC power. Traction currents flow into the vehicle through the catenary or the third rail, and then back to the negative terminal of the traction substation by the running rail [2], [3]. Section insulators are used near each traction substation to divide the power supply zone into two sections. The catenary or the third rail on both sections will be electrically isolated. Generally, the power supply distance is about 1 to 4 km between two adjacent traction power substations.

Traction current is dynamic due to the variation of the vehicle operation mode, and the mode in a power supply section, including trajectory and movement speed control, is depended on the actual situations [4], [5]. There will be different characteristics reflected on the current waveform when the vehicle is at the state of acceleration, coasting or braking. Meanwhile, the selection of accelerations and decelerations is based on the statistically averages of tractive, resistive and braking forces, which are related to vehicle movement speeds [6]. Due to the complex operation process of the Metro systems, the distribution of the traction current will also be complicated.

Traction current plays important roles in DC railway system in the aspects of accident prevention, fault diagnosis and energy consumption etc. Alawad et al. [7], [8] made a comprehensive summary of the metro accident, part of which was caused by speed control problems. By replicating the true train movement and considering the relationship between vehicle position, speed and time, Zhou et al. [6], [9] established a dynamic simulation model to reconstruct the accident and render suggestions for the accident prevention in high-speed railway system. The speed variation, which is not only
an important parameter in the model but also the cause of accidents, can be directly reflected on the traction current. Many kinds of faults and abnormal operation states, mainly in the form of short circuit fault and overload operation, may occur in DC railway system. Due to these fault conditions, there will be obviously different in traction current and bus voltage [10]–[12]. The increase rate and the steady value of the short circuit current is large when the fault occurs near the traction power substation. The change of the short circuit current is relatively slow when the fault occurs along the line and far away from the traction power substation, due to the effect of the line inductance and resistance [13]. Many fault diagnosis methods based on current analysis have been proposed in previous studies, such as DDL protection method [14], [15]. For this method, the line fault detection is conducted by comparing the current variation ratio and increment in a certain period.

Due to the rapid development of urban railway system, the electric energy consumption is still an unsolved problem that concerned by many researchers. The energy consumption mainly comes from station facilities, such as lighting system, air-condition system and so on, and vehicle traction which consumes most of the electric power [16]. The all-day traction current distribution can reflect not only the characteristics of metro operation, but also the load variations in DC railway system. Proper arrangement of vehicle load schedule will be of great significance to system planning and energy saving. He et al. [17] indicated that the cruising stage can be added before the coasting stage to satisfy the distance and time coordinated control. They proposed an integrated optimization model considering both of regenerative energy and passenger transfer base on the four-stage trajectory control strategy. The relationship between the new vehicle operation mode and the traction current is interesting.

Case studies, which based on the new model and combined by route condition, speed limitation and traction power energy in Nanning Metro Line 1 and 2, were also carried out. Results show that the approach can reduce the energy consumption by approximately 48.25% for Line 1 and 39.80% for Line 2 [16].

Generally, considering the problems such as tunnel insulation etc., the catenary voltage is relatively low. Thus, the corresponding traction current needs to remain relatively larger to provide enough traction power for vehicles [18], [19]. However, a larger traction current will cause some other problems. For example, a higher rail potential will not only endanger life safety but also cause serious stray currents leakage and cause critical corrosion problems [20]–[22]. Field tests have been conducted in some metro stations, such as Taipei Metro, Taipei [23], [24]; Nanjing Metro Line 1, Nanjing, China [25]; Guangzhou Metro Line 8, Guangzhou, China [26]; Milano Subway Line, Milano, Italy [27]; etc. Efforts of these measurements are mainly devoted to the rail potential and the stray current corrosion. Although the traction current was measured in Guangzhou line 8 [26] by combining the actual vehicle operation regulations within a short time period, the variations of feeder current in a whole day have not been studied in detail.

In this study, we have analyzed the 24-h dynamic current variation of both up-line and down-line feeders in one station of Wuhan Metro Line 6. The temporal characteristics of a signal feeder and the interrelation with other feeders, the relationship between the traction current and the rail potential are also presented in this paper. The sections are arranged as follows. Section II gives the introduction of the traction system in Wuhan Metro Line 6 and the arrangements of the field tests. Section III analyses the fluctuated features of feeder currents in different periods. Section IV discusses partly phenomenon and gives explanations for some specific waveform features, and finally conclusions are given in section V.

II. INSTRUMENT AND MEASUREMENT

Fig. 1 gives the network of Wuhan Metro Line 6. As the first metro line supplied by 1500V DC in Wuhan Metro Systems, Wuhan Metro Line 6 is composed of 27 tunnel stations with a total length of 36.1 km and the average distance of 1.37 km between each station. The third reciprocal station of metro line 6, Laoguancun station is a traction power substation (TPS). In our field tests, there are two power supply sections, one is Laoguancun Station to Guobo Bei Station (another traction power substation), another one is Laoguancun Station to Jiangcheng Avenue Station (another traction power substation).

As shown in Fig. 2, the TPS acquires electrical power from the urban power grid, and then, the rectifier transformer will convert the AC voltage to the DC 1500V. There are four feeder lines, 7011; 7021; 7031 and 7041 feeders, among which the 7011 and 7031 feeder lines provide power for...
FIGURE 2. Schematic diagram of the traction system and our measurement setup.

the Down-Line (Laoguancun to Jiangcheng Avenue direction), and 7021 and 7041 feeder lines provide power for the Up-Line (Laoguancun to Guobo Bei direction). The length of two sections are 3km and 2.8km, respectively.

All the feeder lines are situated in the station interlayer and fixed by steel structures. Each feeder line consists of five horizontally arranged cables, each of which carries almost the same currents. In Fig. 2, measurement was carried out on these cables. The rail potential was measured in the over-voltage protection device of the section supplied by 7031 and 7041 feeders.

The field test was started at 16:09 local time, 4th May, 2017, and terminated at 00:06, 6th May. The current was measured by sensors with an output sensitivity of 750A/V, a bandwidth of 0~2000Hz and a maximum measured current peak of 3kA. The sampling rate of data acquisition instrument was 10 per second. In this paper, the 24-hour current waveform of four feeder lines, from 0:00 a.m. 5th to 0:00 a.m. 6th, and related results are analyzed in detail as follows.

III. RESULTS

A. 24-HOUR CURRENT DISTRIBUTION AND IMPULSE CURRENT FEATURES

24-hour current distribution of four feeder lines are shown in Fig. 3. The traction current will be positive when the train is in the state of starting and accelerating, and will be negative when regenerative braking. In Fig. 3, from 00:00-04:00 a.m., the transit system was off the line, and thus there was no traction current signal. However, the current varied around 4:30am, and the whole process lasted for about 1 hour until 5:30am. This period corresponded to the train dispatched before the metro began its operation. Half an hour later, from 6:00 a.m., the current of four feeder lines varied obviously throughout the whole vehicle operation period until around 24:00 p.m.

The variation of traction current under different vehicle operation modes can be reflected from the current waveforms. As shown in Fig. 4, the 24-hour current waveform has been divided into several single panels in every four hours starting from 8:00 a.m., with a time span for each being fifteen minutes. The feeder currents in the same power supply section are put together. Each repetitive segment represents a traction process of vehicles. It can be found that there are four types of repetitive inrush current segments periodically appearing throughout the all-day current waveforms. The segment of 7011 feeder consists of two positive sharp peaks, such as the waveform during 08:02-08:04 a.m. The first sharp wave lasts about for 20 seconds and the amplitude reaches about 2000A. The second sharp wave occurs one minute later and its amplitude is usually smaller than half of the amplitude of the first sharp wave. The segment of 7021 feeder is saddle shaped, consisting of two positive peaks and an anti-peak, such as the waveform during 20:00-20:02 and 20:07-20:09. The time difference between two positive peaks is about 40 seconds and the anti-peak occurs immediately after the second positive peak. The segment of 7031 feeder consists of two double peaks followed by a sharp peak, for which the whole process lasts for about 190 seconds, such as the waveform during 12:10-12:14. Both intervals between two double peaks and between the second...
double peaks and the sharp wave, are about 60 seconds. Normally, the 7031 feeder will reach the positive maximum at this sharp wave. The segment of 7041 feeder consists of two hump shaped waveforms, for which the whole process lasts for about 360 seconds and the interval between the two hump waves is about 280 seconds, such as the waveform of 08:06-08:11. The amplitudes of them remain at the same level, about 2000A.

Each repetitive segment represents a traction process of vehicles. In Fig. 4, it can be found that the interval of every two repetitive segments is about 9mins in some periods, such as the period from 8:00 to 8:15; while in the other periods the interval is 11mins, such as the period from 12:00 to 12:15. Based on this phenomenon, the operation time of the vehicle can be divided into peak hours and off-peak hours. For example, from 8:00-8:15, the two sharp waves of 7011 feeder...
applied at 08:03 once, and 9mins later, they appeared again at 08:12. From 12:00-12:05, this repetitive segment occurred at 12:02 and again at 12:13, the interval is 11mins. By comparing the frequency and interval of repetitive segments in other operation periods, 6:00-9:00 a.m. and 16:00-20:00 p.m. are the peak hours of Wuhan Metro line 6. Vehicles in these hours will operate more frequently than that in the off-peak hours.

B. INTERRELATION OF TRACTION CURRENTS
7011 and 7021 feeder lines are responsible for the power supply in the section from Laoguancun Station to Jiangcheng Avenue Station; 7031 and 7041 feeder lines are responsible for the power supply in the section from Languancun Station to Guobo Bei Station. The feeder currents between different power supply sections during 8:00-8:15 are shown in Fig. 5. Combined with Fig. 4 and Fig. 5, it can be found that 7011 and 7021 feeder currents always keep synchronous variations except for their individual repetitive segments, and similarly, 7031 and 7041 feeder currents have the same features. A comparison of the 7011 and 7031/7041 feeder currents shows, in addition to repetitive segments, their variations are relatively contrary to each other. As shown in Fig. 5, when the 7011 feeder currents increase or decrease, the corresponding 7031 or 7041 feeder currents will keep decreasing or increasing. When the current of 7011 feeder reaches the peak, those of 7031 or 7041 feeders reach the inverse peak. Similarly, the relationship between 7021 and 7031/7041 feeder currents is the same as that between 7011 and 7031/7041 feeder currents.

C. DISTRIBUTION OF TRACTION CURRENTS
Distribution of four feeder currents per hour from 6:00-24:00 are summarized in Table 1, in which almost all the feeder currents are found to be within 2000A. Over 95% of 7011 and 7021 feeder currents range from -500A to 500A during any one-hour period, at least 80% of 7031 and 7041 feeders are in the same range. The percentage distribution of four feeder currents are mainly depended on the occurrence frequency of repetitive segments, since the current values normally remain at lower levels among other parts. For example, a small part of 7021 feeder currents are smaller than −1000A due to the existence of the anti-peaks.

The percentage of the current range of −500A to 500A can also indicate the difference between peak hours and off-peak hours. For example, in Table 1, the percentages of current range of −500A to 500A for 7011 to 7041 feeders are, respectively, 98.7%, 99.16%, 93.58%, 91.52%, during 13:00-14:00, whereas those during 8:00-9:00, they are, respectively, 97.83%, 97.96%, 88.93%, 85.72%. The current distribution during 13:00-14:00 are obviously larger than those during 8:00-9:00. Similar conclusions can be obtained by comparing other peak hours and off-peak hours.

Fig. 6 gives the positive average values (computed by the average of all the positive feeder current) of four feeders for one hour and for fifteen minutes. Firstly, as to one-hour average values, the 7031 and 7041 feeders have very similar evolutions with time, and similar evolution trend can also be found in current of 7011 and 7021 feeders. The average values of 7011 and 7021 feeders mainly ranged from 60A to 120A, and the overall variation trends of them are relatively insignificant. The values during 6:00-9:00 and 16:00-20:00 are slightly larger than those during other periods, but there is a small increase during 23:00-24:00. The average values distribution of 7031 and 7041 feeders have wider ranges. They are all above 100A except for 23:00-24:00 periods. As shown in Table 1, during 23:00-24:00, all the currents of 7041 feeder and over 97.39% of 7031 feeder are smaller than 500A, indicating that the repetitive segments of these two feeders are no longer obvious due to approach of the shutdown time. The difference between peak hours and off-peak hours is more clearly reflected on 7031 and 7041 feeder currents, the average values in peak hours being obviously larger than those in off-peak hours. More details can be found in the fifteen-minute average values. The differences in
averages between various 15-minute periods in an hour can be as high as tens of amperes, as mainly determined by the occurrence time of repetitive segments.

The frequency and positive extremum of the repetitive segments of 7011 to 7041 feeder currents in peak and off-peak hours are shown in Fig. 7. The maximums of 7021 feeder current, ranging from 400A to 1600A, are significantly smaller than the other three feeders. The maximums of the other three feeders are randomly distributed in the interval from 1200A to 2400A, and with a high probability in the range of 1400A to 2000A. Moreover, there are no obvious differences on extremums between peak and off-peak hours, but the repetitive segments generally occur 6 to 7 times in peak hours, while 5 to 6 times in off-peak hours.

D. TRACTION CURRENTS AND RAIL POTENTIAL
The rail potential was measured on the overvoltage protect device of the section from Laoguancun Station to Guobo Bei Station, which is supplied by 7031 and 7041 feeders. Fig. 8 shows the 24-hour rail potential distribution, the overall distribution features being found to be similar to the feeder currents. The rail potential keeps continuous fluctuating when the traction system is operating. The sum of 7031 and 7041 feeder current and rail potential during 8:00-8:10 and 13:00-13:10 are shown in Fig. 9, from which we can find that the rail potential is almost synchronized with current variation, as evidently reflected in the repetitive segments of 7031 and 7041 feeder currents, such as the sharp wave of 7031 feeder at about 13:09:30 and double peaks of 7041 feeder during 8:01-8:02 and 13:08-13:09.

The rail potential distribution from 6:00-24:00 is shown in Fig. 10. The maximum positive rail potential

![Figure 6](image6.png)

**FIGURE 6.** 1-hour and 15-minute average positive current distribution of 7011 to 7041 feeders.

![Figure 7](image7.png)

**FIGURE 7.** The positive extremums and frequency of repetitive segments of 7011 to 7041 feeders during peak hours (6:00-9:00 and 16:00-20:00) and off-peak hours (10:00-11:00, 13:00-14:00 and 21:00-22:00).
during the whole operation period is 39.7V and the maximum negative rail potential is 30.1V. However, there almost exist no potential ranging from $-40V$ to $-30V$ or from $30V$ to $40V$. In addition, more than 85% of the potential did not exceed $\pm10V$.

### IV. DISCUSSION

As introduced above, the traction current is dynamic and can return to the negative pole of the substation by running rails. Field test shows that there is continuous current signal during the whole vehicle operation time. When the vehicle
changes its operation mode, the current will increase rapidly to the positive or negative directions, and can reach several kilo-ampere. When the vehicle keeps stopping or coasting, the current will maintain at a relatively low level that no more than 500A.

The actual traction current waveform can be affected not only by the vehicle operation mode, but also by many running conditions, such as the slopes, bends and vehicle’s operation process. These factors will cause a complicate current waveform, from which is difficult to deduce the accurate features of vehicle operation directly. However, by expanding the current waveform shown in Fig. 4, we found that the four feeders of up-line and down-line on the both sides of the power supply section have obvious repetitive segments. Although the up-line feeders (7021 and 7041) or down-line feeders (7011 and 7031) have similar running patents and conditions, the characteristics of the repetitive segment between them have significant differences. Except for these repetitive segments, we found that the currents of up-line and down-line feeders in the same power supply section agree well with each other. This phenomenon is supposed to be reasonable because the recently built traction system is all-parallel power supply, and the up-line and down-line in the same section are connected. Thus, the current variations are similar when there is no vehicle operation.

According to the specific features of repetitive segments, we can make sure that the traction mode of each feeder itself remain unchanged. The interval, which begins from the former repetitive segment and ends before the next repetitive segment, represents a complete vehicle running process. By calculating the beginning and ending time of the intervals, we have divided the operation time into peak hours and off-peak hours. When the traction power remains constant, although the shorter interval will lead to more frequent...
fluctuation in currents, it will not increase the extremums of them. The differences between peak hours and off-peak hours will be mainly reflected in average values. These values in peak hours will be larger than those in off-peak hours.

The non-zero rail potential that exists all the time indicates that there is current flowing out of the feeder through the vehicle and finally into the rail. According to the vehicle operation frequency, there will not always be vehicles running in the section from Laoguancun Station to Guobo Bei station. Therefore, the reason for the non-zero rail potential during the whole operation time can be interpreted as the fact of over zone feeding. The field test in Guangzhou Metro Line 8 indicated that over zone feeding exists widely in DC mass transit system [26]. In addition, the rail potential monitoring point should be in a certain position of the up-line or the down-line. However, the test results show that the rail potential matched best with the sum of 7031 and 7041 feeder currents, instead of one of the two feeders. In electrical traction system, the up-line and down-line are usually connected to balance the currents of two feeders to limit the rail potentials. Therefore, the waveform of rail potential actually reflects the characteristics of both up-line and down-line.

This paper gives a comprehensive analysis of the 24-hour traction current and rail potential characteristics in DC railway system from the aspects of waveform features and energy consumption. All these results can provide certain engineering reference for the next step of related researches. Although all the test results are established on Wuhan Metro Line 6, the analytical conclusion can not only reflect the particularity in Wuhan Metro Line 6, but also reflect the universal regulations of different feeder lines in DC railway systems.

V. CONCLUSION

The traction current, one of the most important indicators of transit system, can not only reflect the load variations in the DC railway system, but also assist in evaluating some negative effects, such as stray current corrosion and excessive rail potential. In this paper, based on an operational metro station, we have analyzed all-day current characteristics of up-line and down-line feeders as well as the rail potential, including the waveform features, the probability and range of distribution, and the related characteristic values.

The traction process of the vehicle operation in different tunnel sections shows a fixed mode, which is related to the actual running conditions. The reflection of this fixed mode on the waveform is periodically repetitive impulse current segment. Except for these repetitive segments, currents of the up-line feeder and the down-line feeder in the same power supply section have similar variation trends. Meanwhile, currents of the up-line or the down-line feeder in different power supply sections have opposite variation trends.

The distribution and the positive average of feeder current per hour from 6:00-24:00 are also analyzed in this study. Results show that the current distribution in off-peak hours is more concentrated in a narrower range than that in peak hours. The differences in averages between various 15-minute periods in an hour is mainly determined by the occurrence time of repetitive segments, and the result can be as high as tens of ampere.

For the rail potential, we found that it has relatively consistent variation regulations with the feeder current. And it matched best with the sum of up-line and down-line in the same section instead of one of the two lines, due to the cross connect of the up-line and down-line rails.

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