A New Protection Method of Metro Traction Electric Lines

Li Ziwei¹, Ning Lu¹*, Wei Yuan¹, Jianrui Zhang¹ and Xingjun Tian¹

¹School of Electrical and Electronic Engineering, Shijiazhuang TieDao University, Shijiazhuang, Hebei, 050043, China
*Corresponding author’s e-mail:18839101136@163.com

Abstract. The recorded operational data shows that the DDL feeder protection malfunction is mostly caused by the unknown resonance in metro traction electric lines. To effectively solve the engineering problem restricting the operation safety of traction power supply, this paper proposes a new feeder protection algorithm based on the feeder current waveform characteristics and the screening principle. The first step of algorithm is removing the working current from the great current by the traditional DDL protection algorithm, and the second step is eliminating the influence of the system resonant current. It is proved by lots of actual cases that the new combined algorithm not only has advantages of clear concept and simple pattern, but also can efficiently identify the short-circuit fault of the traction electric lines.

1. Introduction
The urban rail transit has currently become the first choice for large and medium-sized cities in China to alleviate the public transport pressure, striving to achieve three-dimensional and green urban transport. Unexceptionally, the metro vehicles are the electric vehicles, which indicate the higher requirements for the safety of the traction power supply system (TPSS). The only traction electric lines (TEL) are characterized by the bus-type transportation way, so the metro TEL is more easily to happen the various faults in working than the ordinary power transmission line [1].

Currently, the di/dt-ΔI combined protection, which is also called the DDL protection combined the current change rate algorithm and the current increment algorithm, is usually adopted as the main protection based on the efficient ability in distinguish between load current and short-circuit fault current [2-3]. The recorded operational data shows that the DDL feeder protection malfunction is mostly caused by the unknown and unavoidable resonance in metro TEL. What’s worst is that, all the main efficient transient protection methods are basically invalid for the system resonance [4]. Therefore, it is very important to find an enhanced DDL protection algorithm with eliminating the effects of system resonance, by analyzing the waveform characteristics of the feeder current.

2. Current waveform of metro TEL
2.1. Structure of metro TPSS
The figure 1 is the principle diagram of the metro TPSS. The figure 1 indicates that the metro traction power supply system has some typical characteristics of DC low voltage, bilateral power supply, complex the power supply lines, and moving load, which shows that the fault analysis and protection method about TPSS must consider the power supply property.
2.2. Waveform characteristics of the feeder current.

Figure 2 shows the waveform of the traction load current and the oscillating current recorded by Beijing Metro Line 2.

![Load current waveform](image1.png)
![Oscillating current waveform](image2.png)

Compared with the load current waveform shown in figure 2(a), the waveform characteristic of oscillating current shown in figure 2(b) can be summarized:

- It starts rapidly and has strong impact, evolves into divergent oscillation;
- The initial current value is negative, when the vehicle is in the regeneration feedback state;

3. Feature quantity extraction and recognition algorithm

Figure 3 shows that the process of the combined protection algorithm including the di/dt-ΔI algorithm and the high-order statistical algorithm. The screening principle of new algorithm is that the first step is removing the load current by using the di/dt-ΔI protection (DDL), the second step is eliminating the oscillating current by adopted the high-order statistical protection algorithm.

![Algorithm overall flow chart](image3.png)

3.1. The di/dt-ΔI protection algorithms

The di/dt-ΔI protection is the combination of current change rate (di/dt), current increase (ΔI) and timer (Δt). The three components are based on the current change rate di/dt greater than the set value E as the starting criterion [5]. Once the DDL protection is started, di/dt and ΔI protection enter their respective independent protection identification procedures [6]. When the time Δt reaches the delay time, di/dt or ΔI protection can issue a trip instruction.
In figure 4(a), curve1 satisfies \(\frac{di}{dt} > E\) at the time A, protection starts, and trips at time B after delay time \(T_{set1}\); Curve 2 is normal traction current, since \(\frac{di}{dt} < E\), the protection does not operate.

In figure 4(b), \(E\) and \(F\) are the start and return values of \(\frac{di}{dt}\) protection respectively; \(T_{set1}\) and \(T_{set2}\) are the setting values of current incremental delay; curves1 and 6 are trends of various common currents. Only curves4 and 5 reflect a short-circuit fault on the line.

### 3.2 High-order statistics protection algorithm

When the metro traction system is short-circuited, the feeder current will have a short-term abrupt change process, that is, a singular point is formed, and the oscillating current does not have this feature. The high-order statistics method describes the symmetrical distribution and abrupt change of waveforms by skewness of third-order statistics and kurtosis of fourth-order statistics, so as to construct a combined feature based on skewness and kurtosis, so as to accurately distinguish oscillating current of the system from the short-circuit current.

Step 1: The protection algorithm was introduced. Generally, the waveform of the feeder current can be regarded as a random event, that is, feeder current obeys the distribution law of random variables. If the probability density function of the random variable \(x\) is \(f(x)\), then the \(k\)-order central moment of the random variable \(x\) is:

\[
s_k = \int_{-\infty}^{+\infty} (x - \mu)^k f(x) dx = E[(x - \mu)^k]
\]

(1)

\(\mu = \frac{1}{N} \sum_{i=1}^{N} x_i\) is the average of random variable \(x\), \(N\) is total number of the sample points.

Step 2: Skewness measurement algorithm. The third-order central moment is a numerical feature that measures the degree of asymmetry of the random variable around the mode. Whether positive or negative bias, once the skewness is large, the data is not uniform and does not obey the normal distribution. Dividing the third-order central moment by the cube of the mean square error yields a dimensionless quantity, defined as the skewness parameter:

\[
SK = \frac{s_3}{(s_2)^{3/2}} = \frac{s_3}{\sigma^3} = \frac{\int_{-\infty}^{+\infty} (x - \mu)^3 f(x) dx}{(\int_{-\infty}^{+\infty} (x - \mu)^2 f(x) dx)^{3/2}}
\]

(2)

Step 3: The kurtosis measurement algorithm. The fourth-order central moment is a numerical feature that measures the steepness of a random variable. If the frequency distribution of the sample follows a normal distribution, its fourth-order center moment is 0. Whether the fourth-order central moment is not equal to 0, the data is abnormal and does not obey the normal distribution. Dividing the fourth-order central moment by the fourth power of the mean square error yields a dimensionless quantity, defined as the kurtosis parameter.
Step 4: State feature construction and fault criteria. To quickly and accurately extract the fault state characteristics, define the high-order statistic feature $J(m)$ as:

$$K = \frac{s_1}{(s_2)^{1/2}} = \frac{1}{\sigma} = \frac{\int_{-\infty}^{\infty} (x - \mu)^4 f(x) dx}{\left(\int_{-\infty}^{\infty} (x - \mu)^2 f(x) dx\right)^{2/2}}$$  \hspace{1cm} (3)$$

In summary, a feeder protection method that combines the DDL algorithm with the high-order statistic algorithm is a time domain analysis method, which does not require a high sampling rate and is simple in algorithm. The real-time performance of the combined algorithm is also high. More importantly, the combined protection algorithm extracts both the trend characteristics of the current and the current symmetry and mutation characteristics.

4. Case analysis

4.1. The DDL Algorithm Example

Considering that the starting conditions of the $di/dt$ and $\Delta I$ protection of the metro TEL are the same $di/dt$ setting value. Figure 5 shows calculation result of current rise rate $di/dt$ of traction electric lines load current and short-circuit current.

![Figure 5(a). Traction load current diagram](image_url)

![Figure 5(b). Feeder short circuit current](image_url)

As shown in figure 5, the characteristics of load current and short-circuit current rise rate have the following rules:

- The peak value of the load current characteristic often appears at the transition of the vehicle operating conditions, and the peak value of short-circuit current $di/dt$ characteristic occurs more than about 20ms after the short-circuit fault.

- The $di/dt$ characteristic value of the load current changes little, even in the peak period of metro operation, the critical value does not exceed $\pm 6.0kA/s$; the $di/dt$ characteristic value of the traction system short-circuit current varies greatly, and the maximum can be hundreds or even thousands.

- The characteristic value and characteristic value of the short-circuit current of the traction electric lines do not reach the maximum value at the same time, but the two characteristic values are large, which is not available in the load current.

Compared with the characteristics of the traction electric lines current $\Delta I$ of the metro traction system, the setting value is $4kA$, and the setting value of the $di/dt$ characteristic is $E=60kA/s$. In this way, the DDL protection algorithm can quickly and accurately distinguish between the traction load current and the traction system short-circuit current.

4.2. High-order Statistic Algorithm Example

After eliminating the influence of traction load current, the high-order statistic characteristics of the traction system short-circuit current and the system oscillating current can be calculated according to
equations (3) and (5). The calculation results are shown in figure 6.

![High-order statistic eigenvalue graph](image)

Figure 6. High-order statistic eigenvalue graph

The time series axis (-1~0) in the figure 6 corresponds to the calculation result of the sampling value in the -20~0ms period before the protection starts, and the time series axis (-2~1) corresponds to the time period before the protection starts from -40 to -20ms. The sampled value is calculated, and so on.

It can be seen from figure 6 that in each time series of 200ms before the start of the DDL protection, the short circuit of the traction system of the metro and the oscillating current of the system have the following rules in terms of high-order statistics:

- The characteristic value of the short-circuit current is significantly larger than the characteristic value of the system oscillating current, and the closer to the protection start time, the greater the difference in eigenvalue.
- The characteristic $J(m)$ of the system oscillating current must have a negative value, and the characteristic $J(m)$ of the feeder current changes significantly before and after the short-circuit of the traction system, while the overall variation of the oscillating current of the system is small.
- A regenerative braking phase may also occur during a short-circuit fault, but the first time period before the protection starts is also a large positive value.

It is known from the analysis that the current data of the first time period (20ms) before the start of the DDL protection can be directly used to distinguish the system oscillating current from the traction system short-circuit current.

5. Conclusion

The quality of the feeder protection of the metro TPSS will directly affect the reliability of the locomotive operation. Therefore, it is of great significance to study the short-circuit fault analysis and protection measures of the metro TPSS. In this paper, the mainstream feeder protection technology in the current metro TPSS is summarized. On the basis of retaining the DDL protection algorithm, add the higher order statistic algorithm to form a feeder protection method that combines multiple layers of algorithms. The algorithm can distinguish the short-circuit current from the oscillating current by the high-order statistic algorithm after the DDL protection algorithm distinguishes the normal operating current. The short-circuit fault current is finally obtained. The metro feeder current data measured in the example analysis confirms that the protection method not only can quickly identify faults, but also has clear principles and convenient engineering implementation.

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