Survey of Research on Feeder Line Protection and Fault Location in Urban Rail Transit DC Power Supply System

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Abstract

This paper summarizes the system feeder protection and fault location algorithms for current urban rails. Among them, the system feeder protection is realized by analyzing the current rising rate, current increment, power, energy variation characteristics and using neural network and other algorithms. The fault location algorithm is roughly divided into traveling wave frequency method, fault analysis method and artificial intelligence method. Based on this, it comprehensively compares the advantages and disadvantages of various algorithms, summarizes and induction, and looks forward to the future.

Keywords

Urban rail transit, DC power supply system, Feeder protection, Fault location.

1. Introduction

In order to build a "powerful country with traffic", urban rail transit will be vigorously developed in the next ten years. The safe operation of its power supply system is the basis for ensuring the safety of passengers and the normal operation of locomotives[1]. In order to enhance the reliability of the system, on the one hand, the new protection algorithm can be used to adapt to the extension of the subway line and the increase of passenger pressure, so that the protection device reliable and sensitive action; On the other hand, it should accurately locate faults, quickly overhaul and troubleshoot, and ensure system return [2].

There is no mature fault location device in the practical application of subway traction power supply system at this stage[5], Therefore, this paper simply analyzes the current feeder protection algorithm and comprehensively compares the fault location methods in the current stage. It expects to develop a more accurate fault location algorithm, quickly obtain the fault location, and ensure the safe and stable operation of the system.

2. Feeder Protection Algorithm for DC Power Supply System

The safe operation of the DC traction network is a guarantee of system stability. Therefore, in the current rapid development of rail transit, it is imperative to develop feeder protection algorithms with faster response, better sensitivity and higher reliability.

A variety of faults and abnormal operating conditions may occur during operation. Short-circuit faults are the most common and most harmful faults[6]. It can be divided into positive and negative pole short circuit and positive pole to earth (rack enclosure) short circuit[7], The former's existing protection can be divided into maximum current protection, ΔI protection, di/dt protection[8]and Bilateral joint protection, etc; As for the latter, In [9], the potential difference between the enclosure of the DC equipment and the track return flow may be introduced, and the protection action of the rail potential limiting device is described in detail. In actual operation, in order to ensure that the negative electrode potential is high, the rail potential limiting device has priority for operation, and the voltage frame protection and rail potential limiting device setting values should be properly selected[10].

When a short-circuit fault occurs on the traction network line, the voltage of the line is significantly reduced and the current becomes significantly larger. The protection algorithm can be studied based on the electrical characteristics of the two. In [12] , According to the characteristics that the speed of the current rises rapidly after short-circuit and the amplitude of the change is very large, a DDL($\frac{di}{dt}$、ΔI、T) protection algorithm is proposed. The protection characteristics are shown in Fig. 1 . When $\frac{di}{dt} > E$, and $\Delta I > E_{\Delta I}$, The protection instantaneous action cuts off the short-circuit fault of the line; When $F < \frac{di}{dt} < E$, through the delay to distinguish short-circuit small current and load current, delay time in the T, If ΔI is always greater than $F_{\Delta I}$ and the delay is over, this protection action cuts off the short-circuit fault in the line.

In [13], proposed a protection algorithm based on the voltage and current variation. The algorithm uses the current increase rate as the start-up quantity, the protection start-up delay, and the current and voltage change values at the time. If the value is within the delay period, the value is always larger than the protection setting, protection outlet trip, can quickly and accurately respond to non-metallic faults and some remote faults.

In [14], after considering the introduction of regenerative braking technology into the system, an EDDL algorithm was proposed to distinguish between fault currents and low-frequency oscillating currents. Before the traditional DDL algorithm, the entropy comparison was added. In the literature, multi-scale energy analysis is applied to the energy analysis of the current signal to obtain the multi-scale energy entropy of the feeder current.

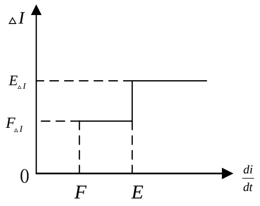

Fig. 1 DDL protection features

In order to solve the hidden trouble that the DDL protection may malfunction when the high-current locomotive starts.In [15], introduces the power balance as the basis of the feeder line protection, and realizes full protection of the whole line without dead zone. In [16], realizes a new criterion of DC feeder protection by means of optical fiber and other communication methods. In [17], taking into account similar locomotive constant torque current and far-end short-circuit current, the Mexh wavelet variation is used to distinguish the two time constants to distinguish the two and avoid the protection from misoperation, which can be used as an effective complement to the $\frac{di}{dt}$ protection.

In [18], the Feedforward neural network is applied to the multi parameter identification of Metro fault signal, the multiple input characteristic quantities are judged together, the optimal criterion is realized, the adaptive ability of feeder protection is improved, and the various running States of locomotive are distinguished effectively.

To sum up, the current rise rate and current increment are the main protection algorithms at the present stage, for the remote short circuit current and locomotive starting current distinguish ability is weak, protection can not identify or cause misoperation. Some conventional tuning methods can be added to the current protection algorithms, or intelligent algorithms can be introduced to make the protection more flexible and reliable. Therefore, the feeder protection algorithm of the system also has a lot of room for improvement.

3. Fault Location of DC Power Supply System

So far, no mature fault location device has been put into the subway operation, and the traditional fault location requires a lot of manpower to patrol along the subway line, which is time-consuming and laborious. It does not meet the requirements of stable operation of the system. Because the structure of the subway is similar to that of the electrified railway, its power supply mode is medium voltage DC power supply. Therefore, the fault location of subway system can be referred to the existing electrified railway and HVDC transmission system[19]. Based on this, the existing subway system fault location can be roughly divided into traveling wave frequency method, fault analysis method and artificial intelligent algorithm.

3.1 Fault Location Based on Traveling Wave Frequency

The fault location of the traveling wave method in the power system is to use the transient voltage generated during the fault. During the propagation process, the discontinuity of the impedance will cause refraction and reflection, and the time difference of the deflexion wave head will be detected to realize the fault location[21]. The accuracy of the algorithm mainly depends on the detection of the wave head and the selection of the traveling wave speed. The method of measuring the variable wave speed based on the broadband fault information can be selected to deal with the problem of the mid-wave velocity in ranging[22].

In [23], selected PSCAD to establish a bilateral power supply DC power supply short-circuit fault model, using the frequency-impedance correlation model in the software to simulate the skin effect of the third rail and the walking rail. Using the multi-signal classification（MUSIC）algorithm to extract the main frequency of the natural frequency at the DC bus of the transformer substation on both sides of the fault line, as shown in formula (1).

$$f_k = \frac{(\theta_1 + \theta_2 + 2k\pi)V_k}{4\pi l}, k = 0, \pm 1, \ldots \tag{1}$$

Thus the fault distance can be obtained:

$$x = \frac{3f_2}{f_2 + f_1} \tag{2}$$

The algorithm only uses two bus voltage values within 25ms from the occurrence of the fault to the protection action, without any other data, and is not affected by the accuracy of the line parameters.However rely on data synchronization between two substations, and it is easy to be affected by short circuit impedance and does not take into account the factors such as locomotive starting or braking.

Compared with HVDC systems, the urban track system has a short distance and a low voltage level. The traveling wave process may not be obvious, and the structure of the contact network in the subway line is complex and contains many places where the wave impedance is not continuous, such as segmented insulators, line fork, etc.; the noise of the actual running urban track is large, and the communication requirements for the line are very high.

3.2 Fault Location Based on Fault Analysis

The positioning algorithm based on fault analysis is to establish an equivalent short-circuit fault transient model based on the relevant parameters of the known system, write differential equations, and find the fault distance x(Percentage of distance A to AB). When a short-circuit fault occurs in the system, 80% of its short-circuit current comes from the nearest two substations[24]， The model that can be established from this is shown in Fig. 2.

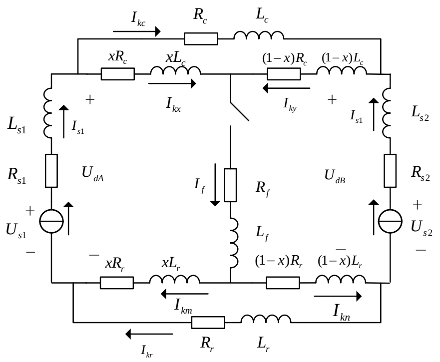

Fig. 2 Transient Model of Short Circuit Fault in Traction Power Supply System

In [25], An empirical method for on-site testing of the Guangzhou Metro Line 2 was proposed. In this method, the distance equation is obtained by using the maximum short-circuit current measured by traction AB, that is,

$$\frac{I_{k1}}{I_{k2}} \approx \frac{1-x}{x} \tag{3}$$

When the method is used in the field measurement, its near-end short-circuit error can reach 10%, which is unfavorable for the staff to eliminate the fault in time. In [25], A theoretical derivation of this empirical formula was made, This empirical method is obtained when the two short-circuit voltages are approximately equal. However, when the fault point is close to a certain point, the voltages of the two are greatly different. Therefore, the improved ranging formula is as follows (4) As shown, the simulation and practice prove that the error is $\pm 60m$, improving the accuracy of ranging.

$$\frac{I_{k1}}{I_{k2}} \approx \frac{1-x}{x} \frac{V_{dA}}{V_{dB}} \tag{4}$$

In the field test, the data recording time of two substations will always have a time difference Δt of several milliseconds. When two unsynchronized voltage and current data are used, the calculation error will increase, and fault fast and accurate positioning cannot be achieved. To ensure data synchronization. If the time difference Δt of the two substations is known to be known, the data of the first trip A and the data of the time Δt before the trip B can be used, and the fault distance can be obtained according to the formula (4)[26].

In [27], on the basis of the differential equation of the circuit column in Fig. 2, according to the equation of the difference of voltage between the two ends of the fault, we convert it to the sampled difference equation, obtain the matrix equation $l = A^{-1}B$ of the fault distance l, and finally use the least square method to get the optimal fault distance. This algorithm has less computation and no filtering processing, but requires high data of synchronization and traction network parameters. Using a near-end short-circuit data validation, the error can be to 48.88%, not suitable for near-terminal short-circuit.

In [28], from the two substations to collect n voltage and current sampling points, the least squares method is used to calculate the resistance value and inductance value on both sides of the short-circuit point, and the fault distance is obtained, as shown in the formula (5). This algorithm can effectively reduce the impact of the transition resistance. At the same time, because the left and right sides of the data are calculated separately, the data is not affected by the lack of synchronization. But because of differential substitution differential, near-end fault location relative error can reach 22%.

$$l = \frac{\hat{R}_{\text{左}} - （1+k）R_f}{r_1 + r_2} \tag{5}$$

In [29], first uses the wavelet packet-SOM neural network to extract the short-circuit current characteristics, establishes the distributed parameter model, and obtains the fault position matrix equation $Ax = Y$. Considering that the rails are susceptible to the skin effect, it can cause the parameter error of the traction network, establish the adaptive function of catenary parameter, and make use of the voltage equality at both ends of the fault point, propose the parameter adaptive algorithm based on the search method, as shown in the formula (6), calculate each ω_j, choose the minimum value as the current fault distance. This algorithm fully utilizes two data and has a large computational load.

$$\omega = \sum_{j=0}^{j=100} (U_{f1j} - U_{f2j})^2 \tag{6}$$

The fault analysis method needs to establish an equivalent fault transient model, write the time-domain differential equations, use the data recorded by the two substations, and solve the optimization equation to obtain the optimal fault distance. Such methods rely on the communication technology of urban rail transit and are susceptible to noise interference in actual operation. It can be seen that such algorithms need to be improved.

3.3 Fault Location Based on Artificial Intelligence

Because of the fault location based on traveling wave frequency and fault analysis, the error is very large under certain conditions. Therefore, relevant scholars have introduced intelligent algorithms to the fault location of DC power supply systems, of which genetic algorithms and particle swarm algorithms are representative.

In [30], considering that the parameters of the traction network only give the approximate range, the genetic code is written using the Matlab/GADS genetic algorithm toolbox by establishing the objective function. Enter the parameter range and data in the substation into the program to obtain the fault location. The algorithm calculated by simulation, the average error is only 2.15%, which verifies the feasibility of genetic algorithm for fault location of DC power supply system.

In [31], considering that there is no communication condition between two substations, a genetic fault location algorithm based on single data is proposed. By analyzing short-circuit current, make the voltage ratio of two substations is constant, and the fault distance equation is deduced,The $u_1(k)$ obtained is compared with the measurement value $U_1(k)$ of its A substation TV. The optimization equation is established as shown in formula (7), and the genetic algorithm is used to solve the problem. Through the simulation calculation, the error distance is about 24m, which can well meet the positioning requirements.

$$\min \frac{\sum_{k=1}^{N} \left[U_1(k) - u_1(k)\right]^2}{N} \tag{7}$$

In [32] in traditional particle swarm optimization, crossover operations are added to preserve the optimal solution. Substituting the best individual in the last iteration for the next round of arbitrary individuals, so that each time the optimal solution is continuously increased, so that the iterated fitness function continuously approaches the signal obtained, and the best function value is obtained Fault distance. The algorithm enhances the particle's search ability. Simulation results show that the improved algorithm accelerates the convergence speed, and the number of correct solutions is increased by about 10% under multi-terminal conditions, which makes up for the local convergence problem.

In [33], considering the orbital skin effect, a least-squares method with genetic factors is used to estimate the varying resistance-inductance values, and then the global optimization of simulated annealing is used to find the optimal result of the search as the initial value of the least-square method. Iterate to find the fault array L, and find the average fault distance. It can be obtained through simulation calculation that the error is only 0.6%, which meets the fault location accuracy requirements.

In summary, fault location based on intelligent algorithms has high fault tolerance and can be applied to distribution networks and urban-rail power supply networks with mixed AC and DC power supply[32]. It is not easy to be affected by the fault distance and the transition resistance[33], but it has a large amount of calculations and its iterative operation speed is slow.

4. Summary and Prospects

At present, the current rise rate and current increment are the main protection of DC power supply feeder in China. With the extension of lines and the increase of passenger traffic, protection based on current characteristics may have application limitations. Therefore, the introduction of multi-parameter common judgment or the combination of multiple intelligent algorithms is the trend of today's urban rail feeder protection algorithms.

The DC power supply fault location algorithm in China is still in the initial research, and some of its current problems are as follows:

The traveling wave frequency-based fault location algorithm is limited by subway lines and structures, and is susceptible to noise during operation. This algorithm may not be of great significance to actual engineering.

Positioning algorithms based on fault analysis simplifies the actual parameters, and are highly dependent on the communication technology between the two substations, resulting in a large measurement error at the short circuit at the near end.

Based on the artificial intelligence fault location algorithm, through continuous iteration to solve the optimal fault distance, relatively speaking, its large amount of operation, the speed is slow.

With the development of artificial intelligence, fault location algorithms based on artificial intelligence have great advantages and are suitable for urban orbits with complex operating environments. The algorithm research will be the main research direction for fault location of DC power supply systems. Combining its ideas with hardware, it is expected to develop a mature DC fault location device to further develop rail transit and build a Chinese-style “powerful country with traffic”.

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