Research on Feeder Protection for a Traction Network Based on Adaptive Parameter Calculation

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Abstract

The feeder protection system is an important part to ensure the safe operation of traction power supply systems. Research on the feeder protection of traction network based on adaptive parameter calculation to analyze its characteristic can apply adaptive protection in the feeder protection better. Specific approach is: Firstly, the harmonic components of the feeder voltage and current value can be calculated with a Fourier algorithm, and then the impedance value and comprehensive harmonic content value can be calculated. Finally, the system parameters are set according to the theory of adaptive protection, whether there is a fault can be determined by monitoring the current state. After analyzing the data generated by the protection program and simulation model, it was shown that the feeder protection method based on the adaptive parameters can quickly distinguish the normal and fault conditions. Compared with traditional protection methods, adaptive protection method is simple, reliable, and easy to maintain, and it can effectively reduce the error.

Keywords: traction power supply, traction network, adaptive parameter, feeder protection; harmonic calculation

1. Introduction

The benefits possessed by rail transportations are safe, economical, fast, environmental and etc, which are incomparable among the others. Railways general use electric traction locomotive as a means of transport, and the electric locomotive is fed by a traction power supply system through the traction network. The load current of the traction network is obviously different from that of the common power grid [1]: a. Traction load current is pulsating high current. b. The traction load current contains a lot of harmonics. c. The magnitude of the traction load current is often close to the short circuit current in the far end. In the traction power supply system, power supply, traction transformer and other important parts take the strategy of redundant backup. However, the traction network has no backup, and its failure rate is the highest. Therefore, whether the traction network can work properly is very important for the reliability of railway power supply.

Adaptive protection is a new type of relay protection, which appeared in 1980s with the development of microcomputer protection [2, 3]. The setting value of conventional protection is set in advance and maintained in operation, while the adaptive protection can change the setting value and even protection principle according to the change of state in the running of the system, which greatly improved the reliability of relay protection. The application of adaptive protection in the over current protection of smart grid was proposed by [4]. [5] put forward the adaptive criterion protection, according to different fault signals to change the protection strategy. Adaptive fault location was proposed by [6]. [7] applied the adaptive principle to shunt reactor compensation.

At present, the feeder protection of electric power systems usually uses distance protection as the main protection, and distance protection is also usually adopted as the main protection of traction networks, and researches at home and abroad are mostly based on distance protection [8,9]. More and more research results of new types of relay protection based on the change of current and voltage have been put forward with the rapid development of microcomputer protection in recent years [10]. These new principles mainly include the principle of adaptive distance protection [12-15], the principle of power frequency variation distance protection [16, 17], the principle of traveling wave based distance protection [18-21], the principle of switchable distance protection, and the principle of over current element with harmonic suppression distance protection [22]. [12] and [13] use the neural network algorithm and ant colony algorithm, respectively, to make the adaptive distance protection more reliable and more intelligent. Based on the geometric characteristics of the measured voltage and current, the effective protection in high resistance was achieved in [14]. The adaptive principle proposed by [15] reduced the adverse effects of power swing on relay protection. By analyzing the variation of the parameters in the interval of the fault, the fault location was effectively realized in [16]. [18] usedg traveling wave polarity information to distinguish external and internal faults and to avoid a voltage dead zone method. [19] proposed a novel protection

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by using voltage fault component polarity to judge the fault line. [20] put forward the method of using a wavelet transform to extract signals, which makes the communication of traveling wave differential protection decrease, and the sensitivity of the protection improved. [22] put forward a kind of protection about an unsymmetrical earth fault, which was based on traveling waves.

The adaptive protection is considered as the subject of this study, where the basic principle is analyzed, and the used method and protection effects are studied by an established calculating program and simulation models. As a result, it proves the benefits of adaptive protection applied to feeder protection.

2. Traction Power Supply System

At present, modes of power supply usually used in traction power supply systems directly feed systems such as direct feeding system with return wire(DN), booster transformer feeding system(BT), autotransformer feeding system(AT). Among which the modes of DN and AT are more widely used. Because these two power supply methods used the same feeder protection principle, the feeder protection of DN was researched as the object only. [23] introduced the traction power supply system in detail, and there is only the introduction of several main parts of the traction power supply system.

As is shown in Figure 1, the power supply mode of DN added a return wire parallel with the traction network, and for every certain , a connection wire is set to make the return wire and rail parallel.

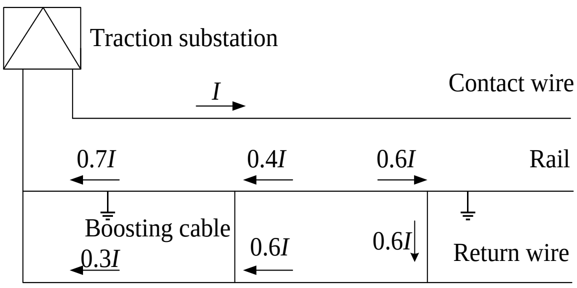

Figure 1: Diagram of DN power supply system

Three-phase AC 220kV or 110kV current is transformed into 27.5kV single-phase AC current through the traction transformer of traction substation. The fast moving locomotive is powered by a traction network. A traction network includes feeder, contact wire, return wire and neutral section insulator. A feeder is used to connect with the pantograph of locomotive, and return wire parallel to the rail and return current, and a neutral section insulator separates the two phases of power supply region, so that the locomotive can pass smoothly. Section post (SP) is usually located in the division of adjacent power supply section, which is used to connect the two feeding sections. In this way, after a power is cut in one side when a fault occurs, the other side can cross the power supply. Therefore, the power supply flexibility and the operation reliability are increased.

3. Adaptive Feeder Protection

3.1 Characteristics of Traction Load

Traction network feeder protection generally uses distance protection as the main protection and current breaking protection as an auxiliary protection.

The traction power supply is a single phase system, and compared with the conventional power system, distance protection has no process of phase selection. However, their loads are quite different, and, mainly, the traction load current has a lot of harmonics, moving at a fast speed; and when closing the switch after the pantograph passing through phase separation, there will be an inrush current.

3.2 Adaptive Distance Protection

In Figure 2, there are two kinds of operating characteristics [24]. Impedance of the protected wire is measured by an metering unit, and the protection will take action if the measured impedance falls in the area.

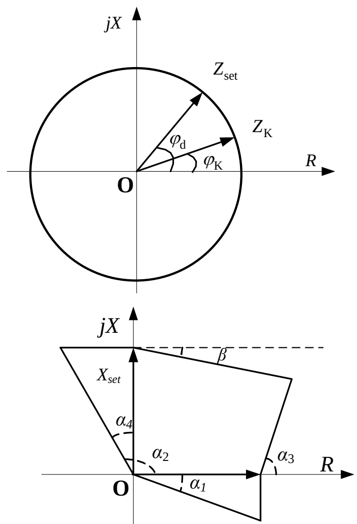

Figure 2: Circle and polygon operating characteristics of distance protection

The action characteristic of quadrilateral impedance elements in Figure 2 can be described as:

$$\begin{cases} R_k \tan\alpha_1 \le X_k \le X_{\text{set}} \\ X_k \cot\alpha^2 \le R_k \le R_{\text{set}} + X_{\text{set}} \cot\alpha_3 \end{cases} \quad (1)$$

In (1), R_k——measured resistance;

X_k——measured reactance.

The polygon action characteristic of impedance elements is a combination of impedance action characteristics, which is composed of a variety of reactance action characteristic, resistance action characteristic and broken line action characteristic. These action characteristic can be designed and adjusted according to the actual needs.

Adaptive distance protection, main protection of feeder protection, can adjust the setting values dynamically according to the current harmonic content. To introduce the research object, comprehensive harmonic content (K_Σ) should be introduced firstly [25]:

$$K_\Sigma = \frac{I_2 + I_3 + I_5 + I_7}{I_1} \tag{2}$$

where I_1, I_2, I_3, I_5, I_7 are fundamental waves and second, third, fifth, seventh harmonics, respectively. The reason third, fifth and seventh harmonics are selected is these three odd harmonics are highest in load currents, and second harmonic happens when closing the switch after the pantograph passing through a phase separation; there will be an inrush current which contains large amount of second harmonic. The setting values are adjusted according to the comprehensive harmonic content:

$$\begin{cases} R'_{set} = \dfrac{1}{1+K_\Sigma} R_{set} \\ X'_{set} = \dfrac{1}{1+K_\Sigma} X_{set} \end{cases} \tag{3}$$

where R_{set} and X_{set} are resistance and reactance setting value, respectively.

The action characteristic of adaptive feeder distance protection is shown in Figure 3.

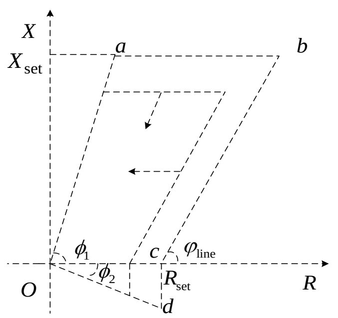

Figure 3: Adaptive distance protection operating characteristic

In Figure 3, φ_1 is a deviation angle to avoid an inrush current. φ_2 is a capacitive deviation angle. φ_{line} is impedance angle of wire. The characteristic boundary changes with the comprehensive harmonic content. Its action characteristic equation is:

$$\begin{cases} 0 \le R \le \dfrac{1}{1+K_\Sigma} R_{set} \\ -R\tan\phi_2 \le X \le 0 \end{cases} \quad \text{or}$$

$$\begin{cases} 0 \le X \le \dfrac{1}{1+K_\Sigma} X_{set} \\ X\cot\phi_1 \le R \le X\phi_{line} + \dfrac{1}{1+K_\Sigma} X_{set} \end{cases} \tag{4}$$

3.3 Adaptive Current Instantaneous Trip Protection

The traction current is sometimes close or even larger than the short circuit current of traction network. In the current instantaneous trip protection, the integrated harmonic content is also used to set the adaptive parameter. Adaptive current instantaneous trip protection equation is as follows:

$$\begin{cases} I_1 - KI_\Sigma \ge I_{set} \\ \dfrac{I_2}{I_1} < K_{2.set} \end{cases} \tag{5}$$

where I_1 and I_2 are the fundamental and second harmonics. $K_{2.set}$ is the setting value of second harmonic content. I_Σ is the comprehensive harmonic current.

3.4 Configuration and Setting of Feeder Protection for Traction Network

The protection object of the research is the feeder of a double track railway, which is shown in Figure 4. This power supply can decrease the voltage drop in the normal operation of the traction network, increase line capacity and reduce power loss. It can be seen in Figure 4 that the two wires end of this section are parallel. In normal operation, the circuit breaker of 1QF, 2QF and 3QF are closed.

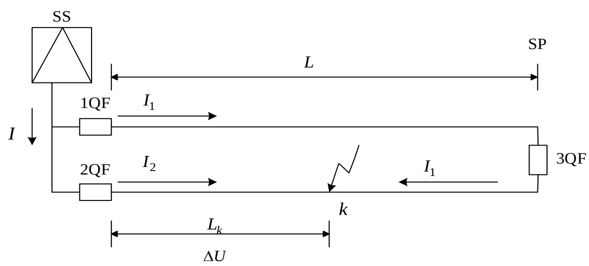

Figure 4: Diagram of double line power supply

3.4.1 Calculation of Impedance

The line with 1QF is up direction, and 2QF is down direction. Let the self-impedance of traction network per kilometer be Z_1 and mutual impedance be Z_m. Short-circuit point is in the down direction, where L_k is from traction substation, and the voltage drop to traction substation is ΔU. The total magnitude of two lines is I = I_1 + I_2. Let the measured impedance of 1QF be Z_I and 2QF be Z_{II}.

According to Kirchhoff's law, the Z_I and Z_{II} can be calculated. The results are shown in Equations (6) and (7).

$$Z_{\mathrm{I}} = (2L - L_k)(Z_1 + \frac{L_k}{2L - L_k} Z_m) \tag{6}$$

$$Z_{\mathrm{II}} = L_k (Z_1 + \frac{L_k}{2L - L_k} Z_m) \tag{7}$$

It can be concluded from Equations (6) and (7) that the measured impedance is related to locations.

3.4.2 Value Setting of Traction Substation Protection

In the double line power supply, feeder circuit breakers 1QF and 2QF are in traction substation configured distance protection of zone I and zone II and current instantaneous trip protection.

Zone I of distance protection is set by 85% of overall length. As shown in Equations (8) and (9), X_1 is reactance component of self-impedance of traction network per kilometer, and X_m is mutual impedance. K_{rel} is a reliability coefficient, which can take 1.5.

$$X_{\mathrm{set1}} = 0.85L \cdot (X_1 + \frac{0.85}{0.15} X_m) \tag{8}$$

$$R_{\mathrm{set}} = \frac{0.9U_{\mathrm{N}}}{K_{\mathrm{rel}} \cdot I_{\mathrm{L.max}}} (\cos\varphi_{\mathrm{L}} - \frac{\sin\varphi_{\mathrm{L}}}{\tan\varphi_{\mathrm{line}}}) \tag{9}$$

Current instantaneous trip protection setting is shown in Equation (10). K_{rel} can take 1.2. $I_{k.sp.max}$ is the maximum short circuit current of section post.

$$I_{\mathrm{set}} = K_{\mathrm{rel}} \cdot I_{\mathrm{k.sp.max}} \tag{10}$$

3.4.4 Value Setting of Section Post

Feeder circuit breaker 3QF in section post configured distance protection of zone I and current instantaneous trip protection.

Distance protection is set by an overall length, which is shown in Equation (11). The set of resistance edge is the same as Equation (9). K_{rel} can take 1.5.

$$X_{\mathrm{set}} = K_{\mathrm{rel}} \cdot L \cdot (R_{\mathrm{set}} - X_{\mathrm{m}}) \tag{11}$$

Current instantaneous trip protection setting is shown in Equation (12). K_{rel} can take 1.2. $I_{loc.max}$ is the maximum load current of a locomotive.

4. Case Study

4.1 Platform of Data Computing

The calculation program of feeder protection for traction networks was written based on LabVIEW. The protection program is mainly divided into four modules, and its flow chart was shown in Figure 5.

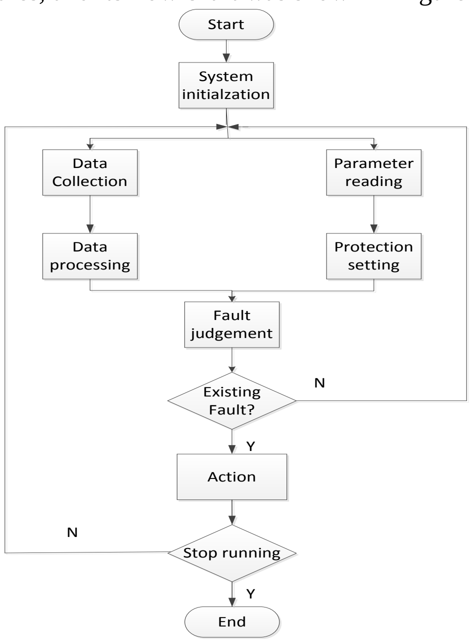

Figure 5: Flow chart of protection program

The function modules of protection program include: harmonic analysis module, setting module, judging module and so on.

4.1.1 Harmonic Analysis Module

This module uses the Fourier algorithm to separate voltage and current in the frequency domain, and then calculate every harmonic frequency and amplitude; finally, the comprehensive harmonic content, measured impedance, voltage and current can be calculated. These data can be used to set the traction feeder protection and fault judgement [26]. Figure 6 is the LabVIEW block diagram of the harmonic analysis module.

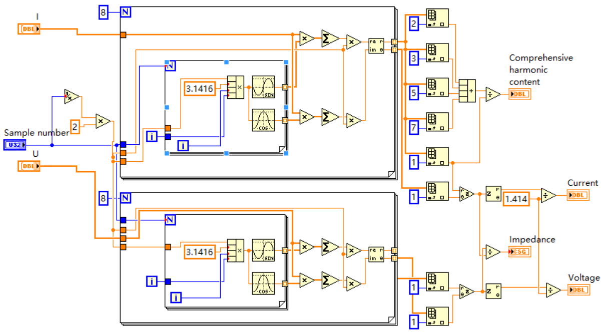

Figure 6: Block diagram of harmonic analysis module

4.1.2 Setting Module

Sub VI setting is the program of setting formulas in the principle of traction network feeder protection. Its function is to calculate the initial parameters and return the protection setting value. The block diagram is shown in Figure 7.

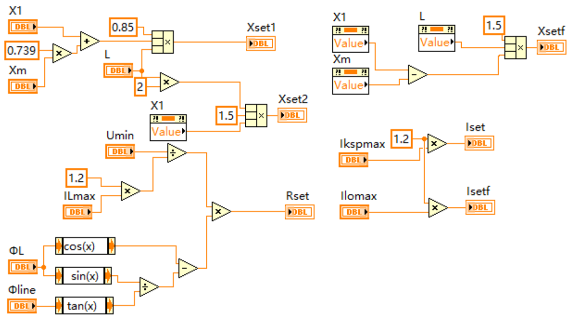

Figure 7: Block diagram of setting module

The meaning of the parameters in Figure 7 is as follows: I_{Lmax} is the maximum load current of the system. I_{Lmax} is the maximum short-circuit current of Section post. I_{lomax} is the maximum load current of an electric locomotive.

4.1.3 Fault Judgment Module

The block diagram of fault judgment module is shown in Figure 8.

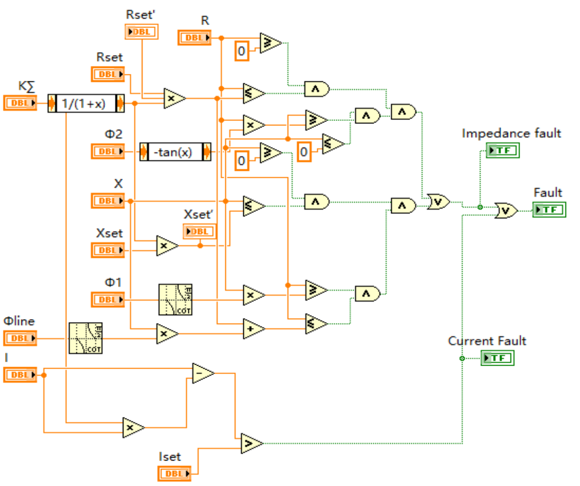

Figure 8: Block diagram of fault judgment module

4.2 Simulation Model of Traction Power Supply System and Electric Locomotive

4.2.1 Simulation Model of Traction Power Supply System

The simulation model of a traction power supply system based on Simulink is shown in Figure 9. This model can simulate a simple fault of the power supply system and the protective action can be analyzed by co-simulation with LabVIEW [27].

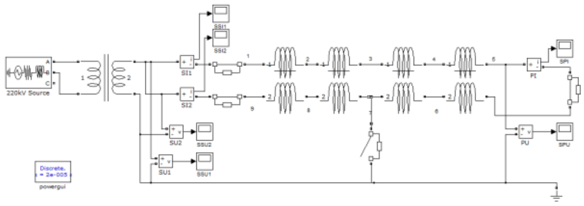

Figure 9: Simulation model of traction power supply system

The parameters of the contact network are derived from a real section. The contact wire model is GLCA-100/215, r_1=0.184(Ω/km), and $R_{\varepsilon f}$=8.57mm. The catenary model is GL-70. When the current is 50A, r_c=1.93(Ω/km), internal inductance x_c=0.45(Ω/km), R_c=5.75mm, and d_h=5800mm. The structure height of a traction network is h=1500mm, and catenary sag is f=600mm. Earth conductivity is σ=10(10^{-4}/Ω·cm). The parameters of a rail are d_g=1435mm, and 50 (kg/m), and the distance of two rail centers is 5m. Based on the data above, the following parameters can be calculated: Unit self-impedance is 0.026+j0.123 (Ω/km), and mutual impedance is 0.026+j0.123 (Ω/km).

4.2.2 Simulation Model of Electric Locomotive

The simulation object of an electric locomotive is Shaoshan SS4 rectifier locomotive, and the model is shown in Figure 10. This model consists of a three winding transformer, a rectifier bridge and two motors. The parameters in rated condition of SS4 are given in [28]：

1) Thyristors T_1, T_2, T_5, T_6 of main rectifier are fully open, and T_3 and T_4 are in state of phase shifting with an angle 39° when electric locomotive working at the sixth level.
2) The counter electromotive force of the traction motor is E=978V, the rectified DC voltage is U_d=1018V, and the DC current is I_d=845A.

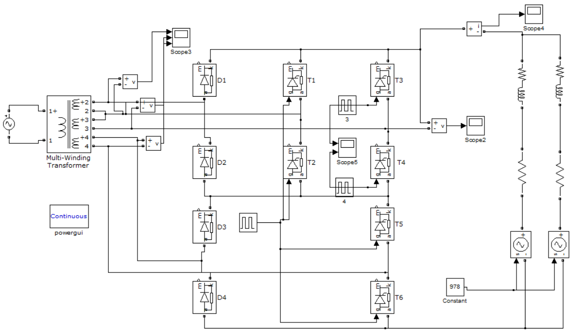

Figure 10: Simulation model of Shaoshan SS4

After the simulation model was built and run according to the above data, its current waveform of the AC side and DC side are shown in Figures 11 and 12.

Current (A)

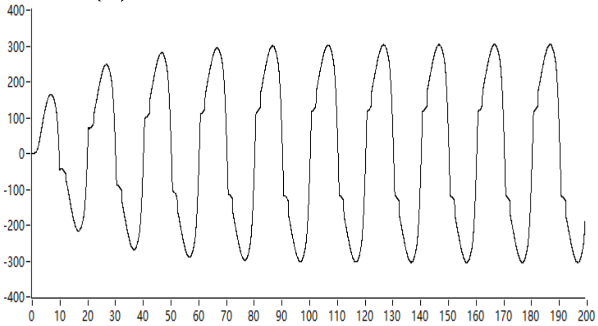

Figure 11: Current waveform of the AC side

Current (A)

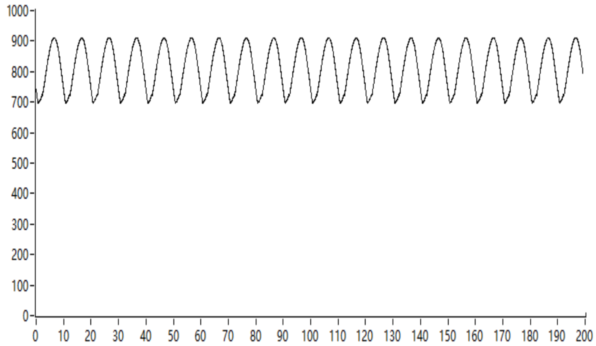

Figure 12: Current waveform of the DC side

It can be seen from the figures that due to the affection of harmonic waveforms, the distortion of harmonic waveforms of AC side is larger while the DC side has slight pulsation. The result as shown in Figure 10 can be obtained by analyzing the current waveform of AC side through a FFT tool of the Powergui. The total harmonic distortion is 30.45%, which is shown in Figure 13, and it is the same as the reality. From Figure 13 and Table 1, it can be seen that the waveform generated by the simulation is in good agreement with the actual waveform, and the practicability of the model is verified.

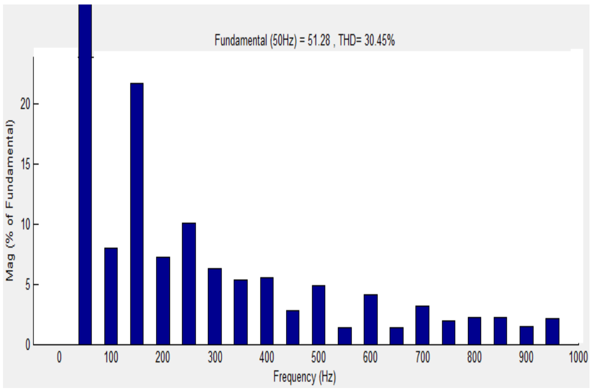

Figure 13: Harmonic analysis of AC side current

Table 1: Harmonic content of SS4 working in the rated state

unit: %

harmonic order	3	5	7	9
simulation result	23.72	11.54	5.06	3.69
Typical statistics	23	12	7	4

4.3 Calculation and Analysis

4.3.1 Initial Condition Analysis

The parameters: X_1=0.648(Ω/km), $\varphi_{line=}$64.7°, X_m=0.123(Ω/km)， L=20km, and φ_L=36.9°, are given. Assume that the maximum load current of an electric locomotive is $I_{loc.max}$=400A; deviation angle to avoid an inrush current is φ_1=75°, and the capacitive deviation angle is φ_2=15°. The short-circuit data measured by the simulation model shows that the maximum short circuit current is $I_{k.SP.max}$=393A. Thus, the zone I distance protection setting value of the substation is X_{set1}=9.50Ω; the value of zone II is X_{set2}=28.08Ω, and the setting value of current instantaneous trip protection is I_{set}=472A. The setting value of zone I distance protection of section post is X_{setsp}=10.35Ω , and the current instantaneous trip protection setting value is I=360A.

The data was measured in relay location when a short circuit occurrence is provided by Table 2.

Table 2: Measurement data for each point of short circuit

Point	1	3
U_{ss1}(V)	19.03∠-58.91°	3500.31∠10.66°
I_{ss1}(A)	951.48∠-58.17°	628.76∠−55.49°
U_{ss2}(V)	19.03∠-58.19°	3500.31∠10.66°
I_{ss2}(A)	0.58∠-116.08°	209.68∠−55.53°
U_{sp}(V)	14.27∠-58.17°	857.63∠1.96°
I_{sp}(A)	0.58∠63.92°	209.68∠124.47°

Point	5	7
U_{ss1}(V)	4987∠-14.11°	3500.31∠10.66°
I_{ss1}(A)	393.45∠-54.77°	209.68∠-55.53°
U_{ss2}(V)	4987∠-14.11°	3500.31∠10.66°
I_{ss2}(A)	393.45∠-54.83°	628.76∠-55.49°
U_{sp}(V)	11.81∠−54.79°	858.76∠1.85°
I_{sp}(A)	11.81∠-54.79°	209.68∠-55.53°

Point	9
U_{ss1}(V)	9.51∠-58.19°
I_{ss1}(A)	0.58∠-116.10°
U_{ss2}(V)	9.51∠-58.19°
I_{ss2}(A)	951.49∠-58.19°
U_{sp}(V)	4.76∠-58.19°
I_{sp}(A)	0.58∠-116.10°

4.3.2 Analysis of fault condition

Take the number 7 of the short circuit point as an example. When a grounding fault occurs, due to the fault occurred in the down direction, the measured impedance of substation is Z_{SS1}=6.74+j15.27Ω for the up direction and Z_{SS2}=2.25+j5.09Ω for the down direction. Measured impedance of section post is Z_{SP}=2.21+j3.45Ω. Besides, zone I of down direction substation distance protection, zone I of section post distance protection and down direction substation current instantaneous trip protection took action, but the others didn't. In Table 3, there is the contrasts of theoretical and actual results. They are very close.

Table 3: Theoretical and measured data

Items	Theoretical value	Measured value	Setting value
U_{ss1}(V)	3500	3501.66	--
I_{ss1}(A)	209.7	209.78	471.6
Z_{ss1}(Ω)	6.74+j15.27	6.75+j15.27	28.48+j9.44
U_{ss2}(V)	3500	3501.66	--
I_{ss2}(A)	628.8	629.08	471.6
Z_{ss2}(Ω)	2.25+j5.09	2.25+j5.09	28.48+j9.44
U_{sp}(V)	858.8	859.18	--
I_{sp}(A)	209.7	209.78	360
Z_{sp}(Ω)	2.21+j3.45	2.21+j3.45	28.66+j10.35

4.3.3 Analysis of Normal Working Condition

According to whether there is a locomotive in the section, the normal state is divided into two kinds of situations. In the short fault condition, it is known that the protection device didn't take action with the absence of fault and locomotive in the section. At this time because the system is open, the measurement impedance is infinite, and the current is infinitesimal. The following focuses on the situation of a locomotive in section.

In order to test the protection device in the situation that traction network working in the normal state with a locomotive, a MATLAB simulation model of Shaoshan SS4 electric locomotive has been established in the first section. The results of the electric locomotive in the point 5 of traction network is shown in Table 4.

Table 4: Simulation results of load in section

parameters	value	parameters	value
Z_{ss1}(Ω)	90.18+j72.29	I_{ss1}(A)	225.3
Z_{ss2}(Ω)	270.28+j216.96	I_{ss2}(A)	75.13
Z_{sp}(Ω)	-269.15-j214.01	I_{sp}(A)	75.13

In this condition, no protection has an action. Besides, since the locomotive load current contains a large number of harmonics, the comprehensive harmonic content is 0.2908. The setting value of the integrated harmonic content is listed in Table 5, in which it can be seen that the setting values became smaller, and the comprehensive harmonic content can be calculated: KΣ=9.50/7.36-1=0.2907. It is very close to the value of system.

Table 5: The comparison of the setting value before and after considered the harmonic content

unit: Ω

Items	R	X_{set1}	X_{set2}	X_{setsp}
Short circuit and no load	28.66	9.50	28.08	10.35
Locomotive load	22.25	7.38	21.80	8.04

5. Conclusions

The principle of the feeder protection based on adaptive parameters was introduced and achieved by the LabVIEW program. According to an actual section for a power supply, the simulation models of the traction power supply system and Shaoshan SS4 were built by using the Simulink. The traction feeder protection principle based on adaptive parameters was calculated and analyzed, and the performance characteristics of an adaptive feeder protection were researched.

It can be seen from the result of the research that the protection method based on adaptive protection parameters can accurately identify the fault current and normal load current, effectively avoiding the malfunction and improving the level of protection of the feeder. The protection method based on the calculation of the adaptive parameters can effectively improve the reliability of traction power supplies.

Acknowledgment

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