# A New DC Feeder Protection Based On Wavelet Transform

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Abstract--This paper presents a new DC feeder protection based on wavelet transform. The model of two substation rectifiers in one track section has been proposed which is according to practical situation. The remote short-circuit current is determined mainly by the steel rail impedance, which is time varying due to the skin effect. In contrast, impedances of the traction motor and the contact wires, and the change of operating mode during starting govern the train starting current. The wavelet transform identifies these salient features. The remote short-circuit current and train starting current are simulated using SIMULINK. The modeling was conducted with respect to the variations of the starting-up process and short circuit conditions. By comparing and investigating the simulation results of short circuit current and the train starting current, more effective algorithms such as wavelet transform has been proposed.

## I. INTRODUCTION

The DC traction system of Beijing Metros is operating at 750V DC obtained from 10kV AC distribution station. In Shanghai and Shenzhen, the voltage is 1500V DC obtained from 35kV AC. Power supply is one of the important systems providing power to not only the trains but also other subsystems and services such as signaling, lighting, ventilation, fire protection, etc. A typical DC traction power supply system is shown in Fig.1:



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In DC railways, the usual assumption of high remote short-circuit currents becomes insufficient, as high traffic density results in heavy train loads. Subsequent studies indicated that the former can have a lower initial rate of change (di/dt) and a longer duration than the typical train starting time. However, some researches [5] show that the methods are incapable of providing sufficiently consistent discrimination between the train starting current and remote short-circuit.

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Fig. 2. Principle of di/dt- $\Delta t$  protection di/dt- $\Delta t$ Point a--- Changing rate of current higher than trip setting level. [Start-up]

Point b--- The changing rate of current between a and b continuously higher than di/dt trip setting level and the duration not less than the setting level. [Trip]

Presently the current relays used in the detection of shortcircuit faults in DC transit systems are based on current magnitude and gradient methods [2, 3]. These relays do not provide reliable detection of remote short circuit faults from the substation especially those of the DC-link fault type that occur within the train units. This is attributed to the similarity of the rise profile of the short circuit current and that of the starting current waveforms.

A wavelet-based signal processing technique is an effective tool for power system transient analysis and feature extraction. The method of wavelet transform is developed for capturing the different dynamic characteristics of the two currents. It is shown to be more effective and reliable than the di/dt comparison methods.

Fig.3 shows the train starting from a nearby substation.



Fig.4 shows a remote short circuit fault occurring between the third rail and return running rails, with no moving train between the substation and fault.



Fig. 4. Model of remote short-circuit

The timely detection of a DC short-circuit fault condition from a normal starting condition has been a common problem in DC transit systems. One such fault is the DC-link fault that takes place within the train. Fig. 4 illustrates the electrical diagram of a typical DC transit system [1]. The arrow in bold print indicates the location of the short-circuit fault that occurs across the DC-link capacitor, within the train electrical compartment.

## A. SIMULINK models for remote short circuit

Because of the skin effects in the steel running rails, The model in Fig. 4 is implemented for the remote short-circuit track impedance, which comprises resistance, internal inductance and external inductance .

The substation with a three-phase rectifier is represented by an equivalent DC voltage source (1500V). The model ignores the tracking line shunt parameters, earth leakage and return path.

The complete SIMULINK model of whole DC transit system which consists of substation, traction load and locomotive subsystem is proposed in Fig. 5.



Fig. 5. SIMULINK model of DC transit system

#### B. Results of simulations

The study period in the SIMULINK simulations is 20 ms.

#### 1) Train starting current

Using the SIMULINK model, which includes the equivalent resistance and inductance according to the fault distance from the substation, the remote short-circuit currents are simulated at two fault locations. Results in Fig.4 exhibit a time-varying time constant for each fault location as revealed by several other researchers.

When the train is being started, feeder line currents at each substation are given in Fig. 6. The simulation is based on the following assumptions:

(i) The track section is based on bilateral power supply system.

(ii) The train is started from substation B to substation A.

(iii) The total length of this track section is assumed to be 2km. As shown in Fig.6, both the current rising rate and current increase when the distance from the substation is decreased. The maximum starting current could be more than three times of the operation current.



Fig. 6. Train starting current of different feeder lines at one track section

## C. Remote short-circuit current

Actual remote short-circuit currents were recorded on the London Docklands Light Rail system [4]. The rising portion of each recording was divided into segments and curve-fitted for calculating the equivalent time constants using the following equation [4]:



Fig. 7. Short circuit current of different feeder lines at one track section

## III. WAVELET TRANSFORM

The feature-extraction process is introduced to enhance the difference in the DC surge profile between the normal

starting and DC-link fault cases. The process takes place only after a surge is detected in the DC waveform. On detecting a surge, continuous wavelet transform (CWT) is performed on the current surge: data contained in the sliding window so as to extract the corresponding feature vector. The function of CWT is clearly different here as compared with when it is used in detecting the surge. The details of the feature extraction function of CWT are explained as follows.

The function by integrating it with scaled and translated versions of the kernel function  $\psi(t)$ . The kernel function is a zero-mean band-pass function with a short-duration cycle, known as a wavelet. The kernel function is similar to the sine or cosine function of the Fourier transform. It takes a variety of forms, but must satisfy the admissible condition in eqn. 4 in the time domain or eqn. 5 in the frequency domain, which means that the kernel function must quickly decay to zero during oscillations. The kernel function has the localisation property that works like a window in the time domain and like a band-pass filter in the frequency domain [6].

$$\int_{-\infty}^{\infty} \psi(t) dt = 0 \tag{2}$$

$$\int_{-\infty}^{\infty} \frac{|\Psi(\omega)|^2}{|\omega|} d\omega < \infty$$
(3)

The modified versions of the kernel function  $\psi_{(a,b)}(t)$ , 'wavelets', are derived from  $\psi(t)$  as:

$$\psi_{(a,b)}(t) = 1/\sqrt{a} * \psi(\frac{t-b}{a}) \tag{4}$$

Eqn. 6 indicates that  $\psi_{(a,b)}(t)$  is *a* scaled and translated version of the kernel function  $\psi(t)$ , and the normalization factor  $(1/\sqrt{a})$  ensures  $\psi_{(a,b)}(t)$ , as the same energy *as* the kernel function  $\psi(t)$ . In the wavelet transform, this kernel function  $\psi(t)$  is known as the 'mother wavelet'. Scaling *a* mother wavelet simply means stretching (or compressing) it, and translating it means shifting it in the time domain. In eqn. 6, *a* represents the scaling factor and *b* represents the time translation parameter. When the scaling factor a > 1 (or a < 1), the mother wavelet is stretched (or compressed). The high scale value therefore corresponds to the low frequency, and the low scale value corresponds to the high frequency. Thus, for *a* given function f(t), its CWT is defined as:

$$W_{\psi}f(a,b) = |a|^{-\frac{1}{2}} \int f(x)\psi^*(\frac{t-b}{a})dx$$
 (5)

where (\*) stands for the complex conjugate. The Mexican-hat wavelet function is defined as

$$\psi(t) = (1 - t^2)e^{-t^2/2}$$
(6)

Thus, for a given function:  $f(t) = \frac{V}{R}(1 - e^{-\alpha t}) \quad (0 < \alpha < 1)$ , its continuous Maxican bet wavelet transform is:

its continuous Mexican-hat wavelet transform is:

$$W_{\psi}f(a,b) = \frac{V}{R}a^{-1/2} \int_{-\infty}^{\infty} (1 - e^{-\alpha t}) [1 - (\frac{t-b}{a})]e^{-(\frac{t-b}{2})^2/2} dt \quad (7)$$

Due to the integral of the mother wavelet equal to 0.

$$\int_{-\infty}^{\infty} [1 - (\frac{t-b}{a})] e^{-(\frac{t-b}{2})^2/2} dt = 0$$
 (8)

Thus, the function of CWT can be expressed as :

$$W_{\psi}f(a,b) = -\frac{V}{R}a^{-1/2} \int_{-\infty}^{\infty} e^{-\alpha t} [1 - (\frac{t-b}{a})]e^{-(\frac{t-b}{2})^2/2} dt$$
(9)

Make  $\frac{t-b}{a} = x$ , so t= ax +b.

$$W_{\psi}f(a,b) = -\sqrt{a} \int_{-\infty}^{\infty} \left[ e^{-\alpha(ax+b)} e^{-x^2/2} - x^2 e^{-\alpha(ax+b)} e^{-x^2/2} \right] dx$$
(10)

According to:

$$\int_{-\infty}^{\infty} e^{-\alpha(ax+b)} e^{-x^2/2} dx = \sqrt{2\pi} e^{(\alpha^2 a^2/2 - ab)}$$
(11)

$$\int_{-\infty}^{\infty} t^2 e^{-t^2/2} dt = \int_{-\infty}^{\infty} t de^{-t^2/2} = \sqrt{2\pi} \qquad (12)$$

$$\int_{-\infty}^{\infty} t e^{-t^2/2} dt = 0$$
 (13)

The wavelet transform result is as follows:

$$W_{\psi}f(a,b) = \frac{V}{R}\sqrt{2a\pi}e^{\alpha^{2}a^{2}/2-ab}\alpha^{2}a^{2} \qquad (14)$$

According to the result, the Mexican-hat transform can make the original wave shows the characteristic of exponential function.

1) Results of wavelet transform



Fig. 8. CWT results of the remote short-circuit current using Mexican-hat transform



Fig. 9. CWT results of the train starting current using Mexican-hat transform



Fig. 10. CWT results of the remote short-circuit current using Mexican-hat transform (scale=7)



Fig. 11. CWT results of the train starting current using Mexican-hat transform (scale=7)

When scale= 7, the scaling factor a=128, the CWT results of the train starting current displayed in Fig. 11 exhibits an exponential function waveform. According to eqn.13, when  $\alpha$  is constant, the waveform of eqn. exhibits like an exponential function, which is conformed with the result.

The CWT results of remote short-circuit current displayed in Fig.10 exhibits a waveform first increases then decreases. According to eqn.13, when  $\alpha$  decreases, the waveform of fig.10 is conformed with the result.

According to the results of the wavelet transform starting current and short-circuit current, it is easy to find the difference between them.

## IV. WAVELET ANALYSIS FOR DISCRIMINATION

In the following analysis, the wavelet results are presented in 3-dimensional displays, in which the x-axis represents the time interval, the y-axis represents the scales, and the z-axis represents the abs of wavelet coefficients.

The CWT results of the remote short-circuit current at 10Km distance from station is displayed in Fig.10, where the wavelet coefficients produce a characteristic surface that exhibits a continuously varying time constant or the short-circuit current.

The CWT results of the train-starting modes are displayed in Figs. 11.



a: chopper has not taken effect b:chopper has taken effect c:with rheostatic

The current magnitude and di/dt comparison methods obviously provide inferior discrimination. If the former method is applied to Fig. 12a, the method will fail to distinguish it from the remote short-circuit current because of the high magnitude of the initial rising part of the curve. If the latter method is applied to Fig. 12a, the method will fail to distinguish it from the remote short-circuit current because of the slow di/dt of the initial rising part of the curve [6].

Based on the above analysis, the wavelet transform is seen to offer a reliable detection of a remote fault by accurately discriminating it from the train starting current.

## V. CONCLUSION

The SIMULINK model offers the waveforms of starting current and remote short-circuit current. The Mexican-hat wavelet transform can reveal the characteristics of the exponential function from these waveforms. Through the analysis of wavelet transform results, the properties of these two currents can be easily identified when scale=7.

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#### VII. BIOGRAPHIES

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