Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Simulation and Algorithm Development of Protection Scheme in DC Traction System

M X Li [1], J H He [1], Z Q Bo [2], H T Yip [2], L Yu [1], A Klimek [2]

[1] *Beijing Jiaotong University, Beijing, China* [2] *AREVA T&D Automation, UK*

***Abstract*--** **This paper presents a simulation model of DC traction system which is based on bilateral power supply mode. The model of two substation rectifiers in one track section has been proposed which is according to practical situation. 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 DDL protection has been proposed. The paper presents the principle and analysis of DDL protection scheme, which shows effectiveness of DDL protection for fault detection and discrimination against train starting currents in the DC transit system.**

***Index Terms*--** **DC traction system, DDL protection, short circuit currents, train starting current.**

I. Nomenclature

DDL means "line fault detection", the main protection of DC railway system. This nomenclature is derived from the French terminology "détection défaut ligne".

II. Introduction

In urban railway traffic systems, the DC traction supply system has been widely used. There are a number of traction electrifications with different voltage levels in DC systems around the world, such as the 600V, 650V, 750V, 1500V and 3000V. The DC traction system of Beijing Metro in China is operating at 750V DC supplied from 10kV AC distribution station. In Shanghai and Shenzhen, the voltage level is 1500V DC and supplied by 35kV AC.

The DC railway is a high density and high capacity traffic system, which develops rapidly. Therefore the importance of security and reliability is beyond doubt and it is necessary to consummate the protection for DC traction power supply system.

The short circuit faults pose a potential threat to safety as well as damage to equipments in DC transit traction power systems. Close-up faults result in short circuit currents with high magnitudes and high rising rate of current. Thus they can be quickly and properly detected. Due to substantial track impedance and relatively low transit voltage with respect to the power demand, remote short circuit fault currents are usually no more than train acceleration currents and train starting currents. Because of the characteristics of DC traction system, traditional protection principles such as instantaneous and time-delayed over-current protection may not be able to produce satisfactory performance. Therefore, it is important to develop better main protection elements that could discriminate the remote short-circuit currents from the train starting currents and could determine the accurate distance to fault location.

III. DC System Configuration

A typical DC railway system is shown in Fig. 1. An AC supply is transformed and rectified to provide the correct DC traction voltage, for connection to the substation positive and negative busbars. Track feeders provide an output connection to the live rails or catenary, through track feeder circuit breakers. The track feeder circuit breaker at each end of a faulted section must operate to isolate the fault.

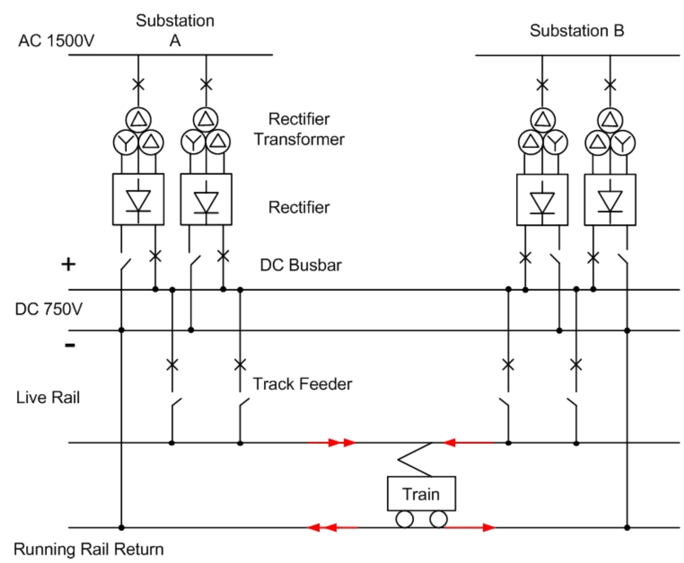

Fig. 1: Typical dc transit system feeding arrangement

Many researches have been done on modeling the DC railway system, but few of them are based on bilateral power supply system which has been widely used for the sake of reliability and security. Therefore, there is a need to extend the previous research by developing a comprehensive and accurate model to simulate feeder line current profile. New algorithms to discriminate train starting current and remote short-circuit current also need to be investigated.

IV. Simulation of Train Starting Current

A. Modeling the traction drive system

SIMULINK is used for modeling the traction drive system. The schematic diagram of DC traction system with a train being started from the nearby substation B to substation A has shown in Fig. 2.

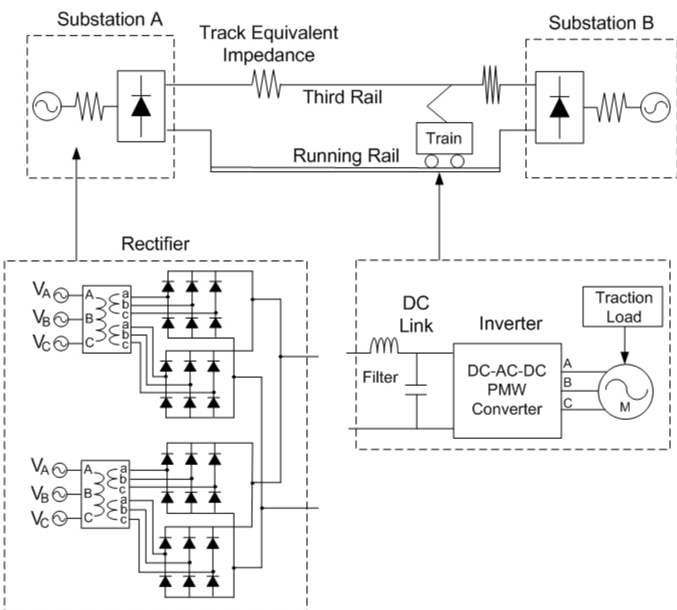

Fig. 2: SIMULINK model of DC transit system

The modeling of DC transit system is implemented based on the following principles:

(i) The track section is energized by two substations. Each substation has two inlet wires.

(ii) Each traction substation has two sets of 12-pulse rectifier units and the winding of two rectifier-transformers have ± 7.5° phase-shifting, to form a 24-Pulse equivalent rectification system.

(iii) Equivalent resistance and inductance are used to substitute the resistance and inductance of the contact wires and the running rails. The equivalent resistances of each side of the train are variable according to the position of the train. An accurate frequency dependent model for the whole track system is proposed by [1].

(iv) A DC-AC-DC PWM converter connecting with a motor is used to represent the electrical, mechanical and control interaction of the locomotive system of train.

(v) The traction load system is derived from mechanical dynamics of the train-wheel-track interactive system which is proposed by [6].

According the schematic diagram, the substation model which includes a rectifier subsystem is proposed in Fig. 3 and Fig. 4.

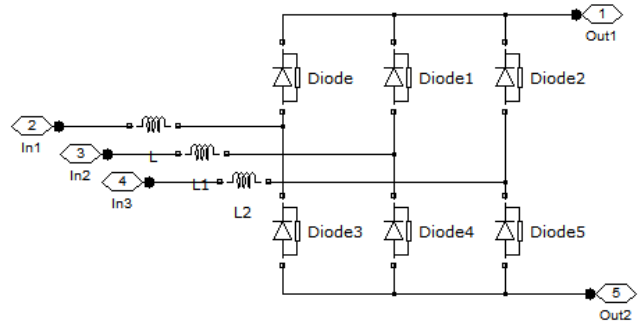

Fig. 4: Rectifier subsystem

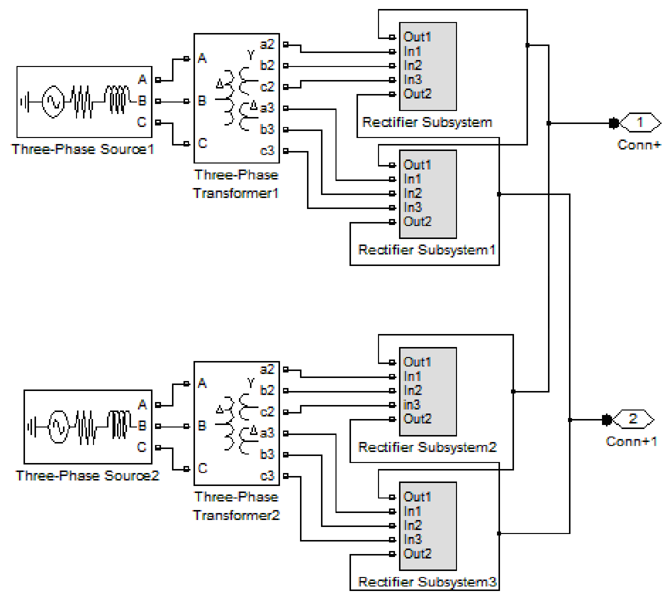

Fig. 3: Substation subsystem

The complete SIMULINK model of whole DC transit system which consists of substation, traction load and locomotive subsystem is proposed in Fig. 5. This model is used to simulate train starting current, short circuit current and train mechanical dynamics.

B. Simulation results

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 increment increase when the distance from the substation is decreased. The maximum starting current could be more than three times of the operation current.

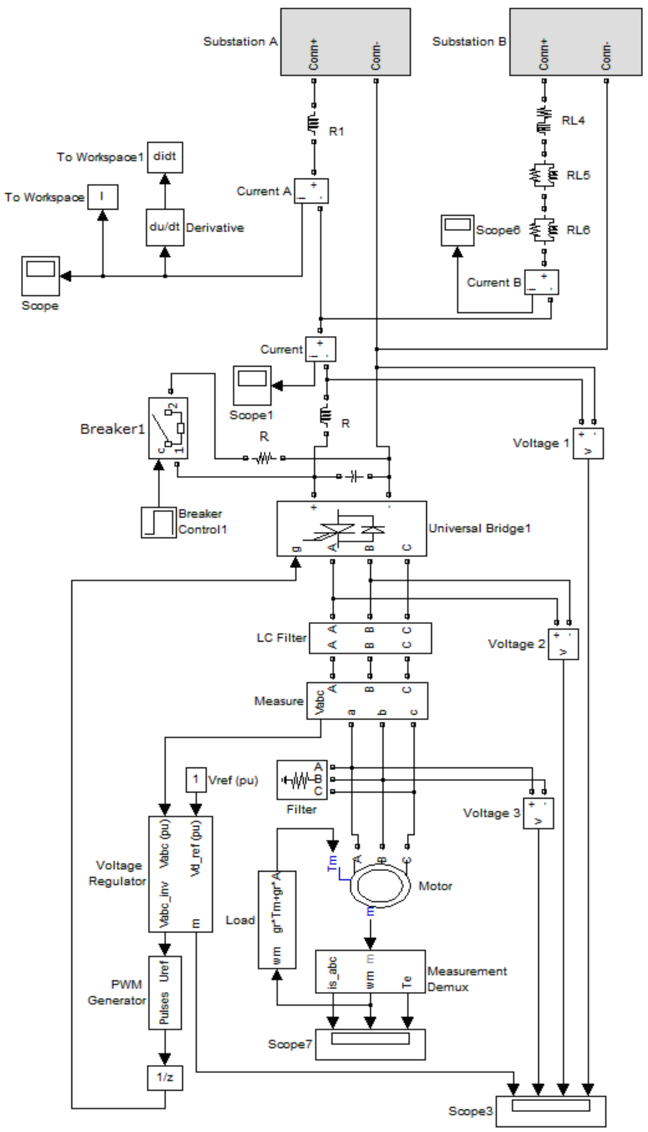

Fig. 5: SIMULINK model of DC transit system

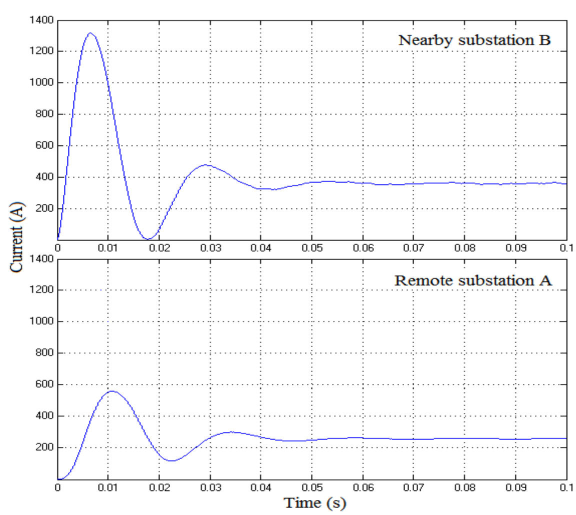

Fig. 6: Train starting current of different feeder lines at one track section

V. Simulation of Remote Short-circuit Current

In order to simulate short circuit fault, an internal fault is assumed to occur across the DC link in the train. As shown in Fig.5, the circuit branch between the DC link represents short circuit fault, the breaker control block is used to give the trigger signal to the switch and to control the time of fault happening.

When the train has started from the nearby substation B and the fault occurs at 0.06s after the train has started, feeder line fault currents at each substation are given in Fig.7.

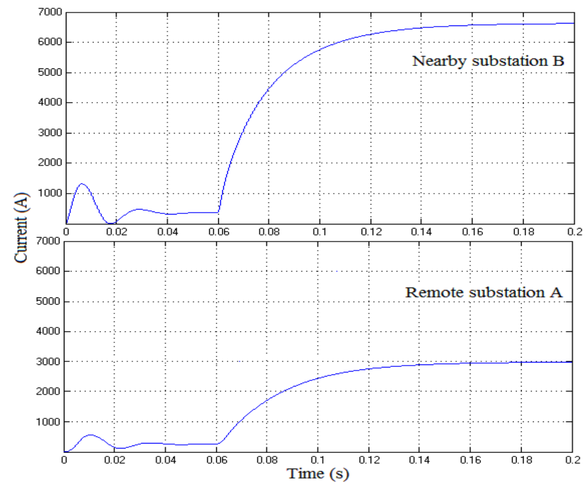

Fig. 7: Short circuit current of different feeder lines at one track section

The curves show that both the current rising rate and current increment on the feeder line at the nearby substation B are higher than the remote substation A.

VI. Analysis of Simulation Results

The relatively low transit voltage with respect to the power demand can mean that fault and load currents are of similar magnitude, and both may exhibit appreciable rates of change. Moreover, if short circuit happens at the end of a long track section, current rising rate and increment of the remote short circuit currents would be less than that of the train starting current. For effective protection of DC railway systems, it is important to clear the remote short-circuit fault as quickly and safely as possible.

Fig. 8 shows the feeder line currents of each substation when a train has started from the nearby substation B and the fault occurs at 0.05s after it started. The total length of this track section is assumed to be 6km.

Comparing the simulation results of short-circuit current in Fig. 8 (a) with train starting current in Fig. 8 (b), it is found that depending on the train location, the increment (ΔI) and rising rate (di/dt) of the fault current can be smaller than that of the starting current of the train owing to the high series-impedance of the traction supply. It is pointed out that the phenomena of mis-operation and mal-operation cannot be avoided with traditional protection which cannot protect the whole feeder line. However, the simulation results indicate that the former can have a lower initial rate of change and a longer duration (ΔT) than the typical train starting current. Base on this finding, it is important to develop better methods that are capable of providing sufficient discrimination between the train starting current and remote short-circuit current.

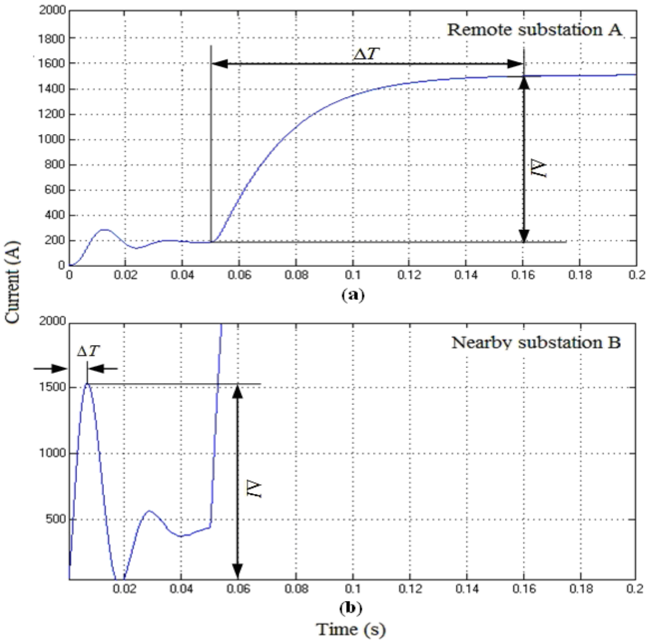

Fig. 8: Current profile of different feeder line
(a) Remote short circuit current of feeder line at substation A
(b) Train starting current of feeder line at substation B

VII. CURRENT RISING RATE AND CURRENT INCREMENT PROTECTION

In resent years, a new technique DDL protection has become the main protection in DC traction system. DDL protection is based on current rising rate (di/dt) protection, current increment (ΔI) protection and delay duration (ΔT). The principles of di/dt protection and ΔI protection are shown in Figures 9 and 10 respectively. In the DDL protection scheme, these two types of protection are arranged to work together, they start with the same rate of change and enter their own characteristics afterwards without interacting with each other.

A. Current rising rate protection

Train starting current has a high initial rising rate, but this is of short duration though the magnitude continues to increase, whereas the distant fault current has a lower rising rate, but continues to rise. The protection has two setting, one for di/dt and one for time duration ΔT , thus allowing the protection to trip the circuit breaker if the high rising rate of the current persists beyond the time setting.

As shown in Fig.9, di/dt protection starts when the current rising rate is higher than di/dt trip setting level at point a within the setting delay duration (ΔT), if the current rising rate is continuously higher than di/dt trip setting level, then a tripping is initiated.

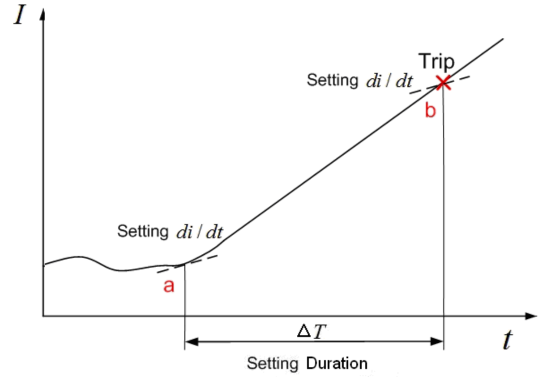

Fig. 9 principle of di/dt protection

B. Current increment protection

This protection is based on the change in magnitude of track feeder current (ΔI) and can be initiated by a di/dt setting.

As shown in Fig.10, ΔI protection starts up at the same time as di/dt protection and enters the delay duration, and then relay protection begins to calculate current increment (ΔI) value. The four waveforms, (1)-(4), represent four different situations:

(1) di/dt and ΔI are higher than the trip setting level with the increase of the step current. However, the duration (ΔT_1) is less than the setting duration (ΔT). Therefore, no trip decision is made.

(2) ΔI is higher than the trip setting level and the duration is longer than the setting duration (ΔT), therefore a tripping is initiated.

(3) In the course of the current rise, di/dt momentarily reduces to below the setting level. However this duration is less than the time setting of protection return (ΔT_{re}), therefore, a trip decision is made.

(4) In the course of the current rises, di/dt is reduce to below the setting level with a duration of more than ΔT_{re} , therefore protection will return.

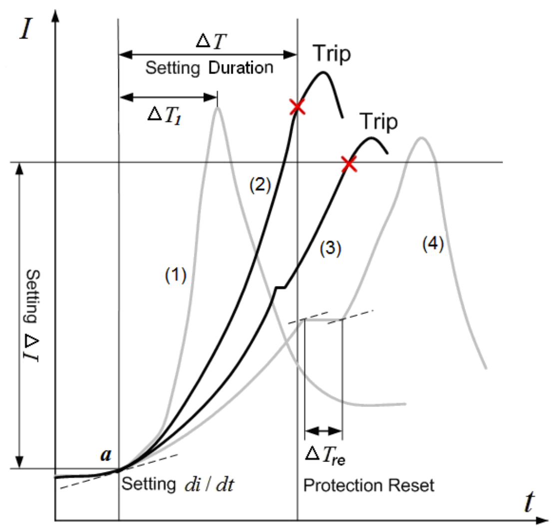

Fig. 10 principle of ΔI protection

C. DDL protection

Investigation on the waveform of short circuit fault current and the starting current indicates that the former can have a lower initial rate of change (di/dt) and current increment (ΔI) but a longer duration (ΔT) than the typical train starting current. Base on the studies of DDL protection principle, it is concluded that the DDL protection can effectively discriminate between the two currents and protect the whole feeder line.

As shown in Fig. 11, DDL protection starts with the setting di/dt at point B. In the protection delay duration, both di/dt and ΔI have been monitored and calculated. Because of the difference in characteristics between start current ant fault current, after the ΔT duration, only the short circuit current could meeting the requirement of the operation zone. Dependability constants K_1 and K_2 are used to improve sensitivity margins of protection in order to protect the whole feeder line.

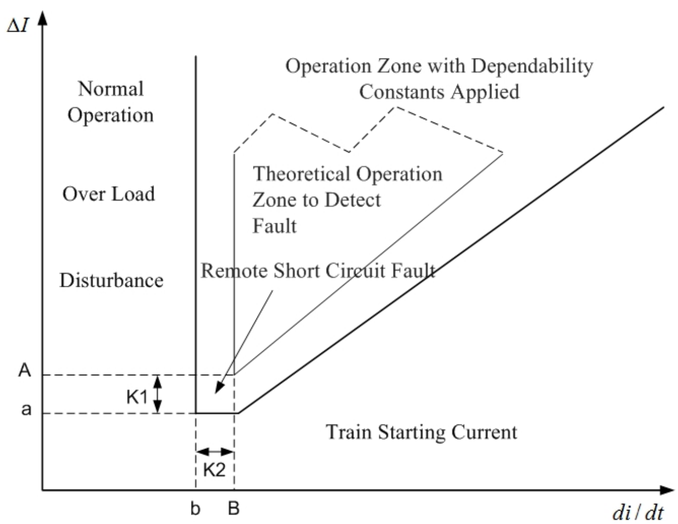

Fig. 11: Schematic diagram of DDL protection

VIII. Conclusion

This paper presents an integrated SIMULINK/MATLAB simulation model of DC traction system which is based on bilateral power supply mode.

Simulation studies were conducted with respect to the variations of the starting-up process and short-circuit conditions. The simulation is based on the whole track section and the results include feeder line current profiles observed from both substations at each section.

By comparing and investigating the waveforms of short circuit fault current and the starting current, the drawbacks of conventional protection have been identified. Simulation was conducted to investigate and assess more effective algorithms for fault detection and discrimination such as DDL protection.

Moreover, based on the studies on the characteristic of the fault current and the starting current, analysis of DDL protection scheme is given, which shows the effectiveness of DDL protection in the DC transit system.

More specific control scheme and algorithms for DDL protection are being developed and will be presented on further work.

IX. Acknowledgment

The authors are grateful to Beijing Jiaotong University and AREVA T&D Automation for permission to publish the paper.

X. References

[1] R. Mathew, F. Flinders, W. Oghana, "Locomotive "Total System" Simulation Using Simulink", Electrical Railways in United Europe, 27-30 March 1995, Conference Publication No.405, IEE 1995

[2] M. FRACCHIA, R.J. HILL, P. POZZOBON, G.SCIUTTO, "ACCURATE TRACK MODELLING FOR FAULT CURRENT STUDIES ON THIRD-RAIL METRO RAILWAYS", pp.97-102

[3] J.C. Brown, J. Allan, "Six-pulse three-phase rectifier bridge models for calculating close-up and remote short circuit transients on DC supplied railways", IEE PROCEEDINGS-B, Vol. 138, No. 6, NOVEMBER 1991, pp. 303-310

[4] J.C. Brown, J. Allan, B. Mellitt, "Calculation of remote short circuit fault currents for DC railways", IEE PROCEEDINGS-B. Vol. 139, No. 4, JULY I992, pp. 289-294

[5] CS. Chang, T. Feng, A. M. Khambadkone and S. Kumar, "Remote short-circuit current determination in DC railway systems using wavelet transform", IEE Proc-Electr. Power Appl, Vol, 147, No. 6, November 2000, pp. 520-526

[6] CS. Chang, A. Khambadkone, Zhao Xu, "Modeling and simulation of DCTransit system with VSI-fed Induction Motor Driven Train Using PSB/MATLAB", IEEE PEDS 2001 INDONESIA, pp. 881-885

[7] Paolo Pozzobon, "Transient and Steady-State Short-Circuit Currents in Rectifiers for DC Traction Supply", IEEE Transactions on Vehicular Technology, VOL. 47, NO. 4, November 1998, pp. 1390-1404

[8] Wei Kong, LiJun, Qin Q Yang, "Integrated Protection and Control, Network Management-Solution for DC Traction Power Supply System", IEE 2004

[9] C.L. Pires, S.I. Nabeta, J.R. Cardoso, "Second-order model for remote and close-up short-circuit faults currents on DC traction supply", IET Power Electronics, 2008, Vol. 1, No. 3, pp. 348 – 355

[10] Alberto Berizzi, Andrea Silvestri, Dario Zaninelli, Stefan0 Massucco, "Short-Circuit Current Calculations for DC Systems", IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 32, NO. 5, SEPTEMBEWOCTOBER 1996, pp. 990-997

XI. Biographies

Moxue Li received her BSc in 2007 in the Department of Electrical engineering and Automation, China Agriculture University. Presently, she is working on her MSc degree in the same field in Beijing Jiaotong University. Her main research interests are Protective Relaying, Fault Distance Measurement and Location in Power System and Traction System.

Jinghan He received her BSc in 1987, MSc in 1994 in the Department of Automation, Tianjing University, China, respectively. Presently, She is employed as a Professor in Beijing JiaoTong University, China. Her main research interests are Protective Relaying, Fault distance measurement and Location in Power System.

Zhiqian Bo received his BSc degree from the Northeastern University, China in 1982 and PhD degree from The Queen's University of Belfast, UK in 1988 respectively. Presently, he is with AREVA T&D Automation & Information Business.

Tony Yip received his M.Sc. in Digital Electronics and Ph.D. in Power System Protection, both from the University of Manchester in 1979 and 1988 respectively. He is a corporate member of the Institution of Engineering and Technology (I.E.T.) and a member of the CIGRE Working Group B5.04. He has been working in the Automation Product R&D Department in AREVA T&D Ltd in Stafford since 1979. His work is mainly related to the development of numerical protective relays. Currently he is a Product

Development Team Leader, responsible for the development of generator, transformer and busbar protection relays.

Le Yu received his BSc in 2006 in the Department of Electrical engineering and Automation, Beijing Jiaotong University. Presently, he is working on his Ph.D. degree in the same field in Beijing Jiaotong University. His main research interests are Protective Relaying, Fault Distance Measurement and Location in Power System and Traction System.

Andrew Klimek is a licensed Professional Engineer with B.Sc., M.Sc. degrees in Electrical Engineering. He has 34 years international experience in the electric power industry and is a member of CIGRE and IEEE. His experience includes a number of positions ranging from university teaching and consulting, to engineering and business management. Andrew has served as a project manager, marketing manager and general manager and has executed various power systems projects. Specifically, he has focused on power generation, transmission & distribution systems, SCADA, automation, protection and control. Cuffently Andrew is the technical Director of the AREVA T&D Automation & Information Business.