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Abstract

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Keywords

traction, system, protection, supply, scheme, dc

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A New Protection Scheme for the DC Traction System Supply

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Abstract—In this paper a new protection scheme for DC traction supply system is introduced, which is known as “overload protection method”. In this scheme, with the knowledge of the number of traveling trains between two traction substations and the value of current which is drawn from each substation, the occurrence of short circuit fault is detected. The aforementioned data can be extracted and transmitted from railway traffic control system. Recently DDL (“Détection Défaut Lign in French”, which means “Line Fault detection”) protection method is used in supply line protection. In this paper, the electrical system of railway system is simulated using the data obtained from Tabriz (located in Iran) Urban Railway Organization. The performance of the conventional and proposed protection schemes is compared and the simulation results are presented and then the practical measures and requirements of both methods are investigated. According to the results obtained, both methods accomplish satisfactory protection performance; however the DDL protection scheme is severely sensitive to the change in components and supply system parameters and it is also hard to determine the setting range of protection parameters of this method. Therefore, it may lead to some undesired operations; while the proposed protection scheme is simpler and more reliable.

Index Terms--DDL Protection Method; Over-Load Protection Scheme; Railway Electrical System; Railway Supply Structures.

NOMENCLATURE

μ	adhesion coefficient
N	normal wheel constant force
M	mass
ω_w, ω_r	the wheel and rotor angular speeds
R	resistance to the train motion
θ	gradient
J	inertia
T_e	motor electromagnetic torque
A, B	static and rotational friction coefficients

I. INTRODUCTION

Along with the economy growth and the metropolitan developments, utilization of railway system has become one

of the key parts of today large cities traffic plan. As railway system is one of the most important solutions for traffic issue in large cities, the occurrence of fault current may lead to delay in the routine operation of trains which in turn may affect the traffic management of city. Additionally, fault currents may results in damaging the electrical equipment and safety devices. Therefore, research on the railway electrical system performance during fault condition has significant importance from the system security and reliability points of view.

In the Direct Current (DC) traction systems, due to relatively low voltage level of the supply line and its high impedance, the amplitude of short-circuit current can be in the order of maximum start-up current drawn from substations. In this condition, fast and appropriate distinguishing between fault current and start-up current is a challenging issue by over-current relays. This condition is worse for short-circuit current occurred far from substations [2]-[8]. In [2]-[12] the modeling and the simulation of the electrical railway system have been fully described. Moreover, in [3] and [4] the new protection method known as DDL has been introduced. In [5] besides introducing different structures of railway supply, the algorithm of the DDL method is evaluated.

Nowadays, DDL protection method is used widely in railway system but its proper operation is extremely dependent to the dynamic impedance of railway electrical system and also the effect of any changes made in the electrical railway system such as supply line, train motors, etc. These effects are already investigated in some literatures [13], [14]. In this paper a new protection method entitling “Over-Load” scheme is proposed. The electrical system of Tabriz railway is simulated and protection performance of DDL and proposed methods is compared by using the data obtained from Tabriz Urban Railway Organization (TURO).

II. THE ELECTRICAL STRUCTURE OF RAILWAY

Different voltage levels including 600V, 650V, 750V, 1500V and 3000V are used as power supply for DC traction systems. In the railway system of Tabriz, a 1500V system is generated from a 20kV power network and is delivered to the train wagons through the Pantograph. According to Fig.1, the

power network voltage level of 20kV is converted to a lower level one through the two three-winding transformers in each substation and with the aid of rectifiers, and thus the appropriate line voltage is generated and finally connected to the supply line. The substation which includes both transformers and rectifiers is referred to as traction substation. It is worth to note that not all the substations are of this kind, and generally the number of such traction substations is

related to the several parameters such as the number of passengers, total power demand, headway and also the number of trains. The output terminals of the rectifiers are connected to the bus-bars and then to the supply line through direct current circuit breakers. These connections are called “Feeders”. There exist two supply lines in this system in which one line is intended for forward traveling trains supply and the next one is dedicated to returning trains.

Fig. 1. Schematic diagram of Tabriz city railway system.

Each traction substation is connected to each line through two circuit breakers and a bypass switch. The DC voltage is delivered to the train through Pantographs. The required three-phase voltage for asynchronous motors of trains is provided by voltage source inverters inside the trains. The motors are controlled using variable voltage and frequency ($V/F=Const.$) method. Moreover, a portion of the train input power is allocated to the internal power consumption in which the required voltage level is generated according to the application.

Due to some special circumstances like malfunction in the operation of the substation, it is possible to supply the trains by one or two substation. Based on the type of energizing the trains, there are different supply schemes including normal, one-sided, bypass and T-form [5]. As seen in Fig.1, in normal scheme all of the circuit breakers are closed and the isolators of substations are opened. Two trains shown in Fig. 1 are located between two traction substations, and their required supply current is provided by both substations. There may also exist one or more non-traction substations, known as auxiliary substation between the aforementioned traction substations.

III. RAILWAY SUPPLY LINE PROTECTION

In the DC traction system, due to the comparable low voltage level of supply line versus line impedance and power rating, the short circuit current magnitude of the fault occurred far from the substation can be in the order of start-up and even the normal operating current of supply line. Therefore, over-current protection system is not reliable and capable of proper and on-time fault detection [2]-[4].

A. The DDL Protection Method

As mentioned in previous section, in order to achieve a proper line protection within a specific range of fault current

close to start-up current, a protection method which is referred to as “DDL” has been already introduced and implemented in the current DC traction systems [3]-[5].

Fig. 2. The flowchart of performance algorithm of the DDL protection scheme [5].

The protection of the system in other cases (beyond the aforementioned range of fault currents) is carried out by the

protection system of circuit breakers which are located between substation bus-bars and supply line. In this method, using several computer simulations, patterns of currents drawn from substations at start-up, acceleration and short-circuit intervals are individually extracted and compared. Finally, by the intention of providing an appropriate security margins, setting ranges are selected and applied to the relevant protection system. The objective of such comparison is to determine the range of parameters including the instantaneous rate of supply line current variation, amplitude variations of the line current and the time length difference of these variations in such a way that all possible patterns of fault, start-up and normal operation currents will be capable of being distinguished and then the appropriate and fast reaction performance could be accomplished by the protection system. The flowchart of performance algorithm of the protection system adapted from [5] has been depicted in Fig. 2.

In this method, if the line current slope (di/dt) exceeds the upper limit setting, the protection system starts to operate so that the initial current value is recorded and within an specific time delay interval ($\Delta T_{setting}$) current slope change is measured. Then, according to the three available current patterns short-circuit is identified and turn-off commands are sent to the switches consequently. In Fig. 3, the performance procedure of protection system for a number of substation current waveform types has been illustrated. The procedure for determination of the protection system performance for the numbered waveforms in Fig. 3 is as follows:

- 1) The amount of current increase and rate of change in current are both greater than setting limits but the occurrence instance of the event (ΔT_i) is smaller than setting time delay interval ($\Delta T_{setting}$) and start-up current is distinguished.
- 2) The amount of current increase, after delay time is passed, goes higher than the limit set, and therefore the protection operation is carried out.

Fig. 3. Protection system performance for different types of current waveforms [4].

If the current slope is lower (or smaller) than the lower limit and also the current increase condition does not hold true, a secondary delay time interval (ΔT_{re}) is also applied and if the current increase condition holds true until the end of second delay and overall past time becomes greater than the

first delay, then the protection operation command will be applied. In the waveform of number (3) in Fig. 3, this condition leads to the protection operation, while in the waveform number (4) the normal operation current is distinguished and the protection algorithm is restarted.

B. Proposed Protection Scheme

According to the DDL protection scheme principle, this method acts based on characteristics of the feeder current waveforms such as start-up current, internal or external fault current, etc. This method has a complex algorithm and also it is necessary to have accurate information about dynamic impedance of the DC traction system elements such as DC supply lines impedance, equivalent impedance of trains, etc. to evaluate the operational settings. In addition, these parameters are inherently variable and sensitive to operation conditions. Therefore, it may have some malfunction in transient states such as acceleration, deceleration and start-stop conditions. In addition, the correct operation of this method depends on the train and the fault distance from substation. Furthermore, it is of significant importance to analyze new structural variations and consider their effects on the protection system operation. In the proposed method these above-mentioned issues are solved, considerably.

In the proposed protection scheme, short-circuit fault is detected and distinguished from train start-up current, with the aid of information about number of traveling trains and sum of supply currents drawn from both sides of the feeders. If the sum of supply currents exceeds a specific value and it lasts longer than a relevant time delay, protection system detects the occurrence of fault and commands to circuit breakers of both sides. Since the fault in this method is detected as an overload for the feeders, it is nominated as the “Overload Protection Scheme”.

Fig. 4. Flowchart of the proposed protection scheme algorithm.

The proposed protection scheme and its operation curve are illustrated in figures 4 and 5, respectively. The maximum allowed steady state current has been assumed to be 4kA. At

the beginning of train moving, start-up current exceeds the maximum allowed current but it quickly falls down the threshold limit. At $t = 0.11s$ a fault occurs and current exceeds the limit again, but this time over current condition lasts more than the pre-set time delay and fault occurrence is detected.

Fig. 5. Substation current and protection operation.

Because of using the sum of both sides' currents in the proposed method, it is independent of the train and fault location between two sides of the feeders. This method has less sensitivity to the system impedance and structure changes. Moreover, this method commands to both sides of lines, while in DDL method each side has an independent protection system.

C. Protection Requirements

Communication and data exchanging requirements can be performed via the SCADA (Supervisory Control and Data Acquisition) system which exists in urban railway systems. The SCADA system is composed of Operation and Control Center (OCC) and Traction Power Substations Automation. In Fig. 6, structure and different parts of this control and command system has been investigated.

Fig. 6. Operation and control center configuration.

It should be noticed that when a train stops in a substation, it does not consume considerable power. Therefore, only the number of traveling trains must be utilized in protection system. Also, maximum allowed steady state current can be estimated and assumed to be constant in protection system with a proper safety margin. This maximum current can be estimated around the nominal train consumption current for

each traveling train; this is because the fault current range is significantly larger than steady state nominal current.

In order to achieve correct operation of both DDL and Overload protection schemes, it is required to discriminate train feeding arrays. For example, in the proposed method, if the feeders of one traction substation are disconnected from supply line, protection system should use the other neighboring substations data. If such a situation would happen in the DDL scheme it will be recommended that the protection settings need to be changed [7].

IV. SIMULATION MODEL

The complete model of the urban railway electrical system consisting of substations, track section and wagons with asynchronous motors has been simulated as depicted in Fig. 7. Each traction substation is modeled as two sets of 12-pulse rectifier units and three-winding transformer of which the secondary windings integrates a $\pm 7.5^\circ$ phase shift to form a 24 pulse equivalent rectification system.

Fig. 7. Schematic of traction substation and train models.

The traction load model is derived from mechanical dynamics of the train wheel track interactive system. The traction force F_{TE} is given by equation (1), and the load torque T_L is given by equation (2). The train and wheel dynamics are calculated by equation (3). The gear ratio, gr is expressed by (4) and the train wheel dynamics expressed with the rotor speed is given by (5), accordingly.

$$F_{TE} = \mu N = M \frac{d(\omega_w)}{dt} + R + Mg \sin(\theta) \quad (1)$$

$$T_L = F_{TE} \times r \quad (2)$$

$$\frac{T_e}{gr} = J \frac{d(\omega_w)}{dt} + B\omega_w + A + T_L \quad (3)$$

$$gr = \omega_w / \omega_r \quad (4)$$

$$T_e = Jgr^2 \frac{d(\omega_r)}{dt} + gr^2 B\omega_r + grA + grT_L \quad (5)$$

Rail tracks and supply line impedance are modeled together as single equivalent impedance and each train is modeled as a VSI inverter supplying asynchronous motor. Also, internal electrical load is modeled as a shunt load with motor.

V. SIMULATION RESULTS

The schematic diagram of the general form of DC traction system is illustrated in Fig. 1. In this model, first train is assumed to be located in non-traction substation C and with 0.84 km distance from traction substation A. Second train is assumed to be located in traction substation B and with 0.88 km distance from substation C. Both trains start to travel simultaneously and at the instant $t = 0.15s$ a short circuit with $400m\Omega$ faults impedance occurs close to the first train.

Substations' currents and DDL protection scheme operation have been depicted in Fig. 8. In Fig. 9, sum of substations' currents and the proposed overload protection scheme operation have been illustrated.

Fig. 8. Current waveform at traction substations A and B using DDL scheme.

Fig. 9. Sum of substation currents using the proposed protection scheme.

After several simulations considering, the worst conditions for railway electrical system, protection settings in DDL are implemented as below:

- Trains start-up current varies between 3kA to 7kA in nominal headway. By increasing the start-up time, the start-up current might decrease to the range of 2kA to 5kA. Fault current range depends on distance from substations and fault impedance. For Tabriz urban railway system, it can be between 2kA to 35kA. Therefore, protection setting current for DDL scheme is proposed to be a little less than 7kA.
- Current slope for starting of operation is 45kA/s. For second current slope, 25kA/s is proposed.

- By considering the rise time of start-up current, first delay time constant is set to 22ms and second delay time is set to 5ms.
- By considering the value of current rising, differential current of 900A is proposed.

Overload protection scheme deals with the sum of both sides' substations currents and it is independent of fault location. The protection settings in the new method are implemented as below:

- Protection setting is less than 12kA.
- Assuming a nominal current of 2.5kA for each traveling train, time delay constant is set to 27ms. According to Fig. 8, the current limiting amplitude is reciprocally related to time delay constant. Therefore, it is quite reasonable to choose compromised constant values for protection scheme.

VI. CONCLUSION

Because of the low voltage level of urban railway supply system and by considering the possible high fault impedance, fault current might be confused with the train start-up current by protection system. The DDL protection scheme is proposed for this kind of faults that deals with current waveform parameters such as current slope and current's peak value. In this paper, a new protection scheme entitled as "Overload protection scheme" was proposed. Both schemes were simulated, evaluated and examined on Tabriz urban railway system. The DDL scheme is remarkably dependent upon parameters of railway electrical system. Also, setting of protection parameters requires accurate information about the electrical elements of railway electrical system. The proposed overload protection scheme has much more redundancy and it has simpler operation. The proposed overload protection scheme in some circumstances had longer time delay. Both DDL and overload protection schemes need to use the railway control and command system.

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