

# DC Auto-Transformer Traction Power Supply System for DC Railways Application

Miao Wang, Xiaofeng Yang, Lulu Wang and Trillion Q. Zheng

**Abstract** In DC railways, the running rails are used as the return path for traction current, which inevitably leads to stray current and rail potential issues with poor insulation. However, the effects of existing solutions are limited, so DC auto-transformer (DCAT) traction power supply system (TPSS) is analyzed in this paper to solve the problems of stray current and rail potential fundamentally. Compared with the existing TPSS (E-TPSS), the mathematical analysis and simulation results show that DCAT-TPSS may solve both stray current and rail potential issues, which further reduce the voltage drop and power loss of power supply lines additionally.

**Keywords** DC railways · DCAT traction power supply system  
Stray current · Rail potential

## 1 Introduction

Nowadays, with the economic development and the growing of population, rail transit systems play a more and more important role in transportation. In DC railways, the running rails act as the return path of traction current. However, the running rails are not totally isolated from the ground, so a part of current leaks to the ground, which causes stray current issue. The stray current results in the electric potential difference between the rails and the ground, which is called rail potential [1–4]. The stray current will not only cause serious corrosion of the underground structures such as reinforced concrete, but also reduce the service life of the pipelines, such as oil and natural gas pipelines, resulting in greater economic losses. Meanwhile, the rail potential will also threaten the safety of passengers and the safe operation of DC railways.

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The main solutions for DC railways to reduce stray current and rail potential include: (1) improving the supply voltage level; (2) strengthening the insulation between the rails and the ground; (3) reducing the rail resistance; (4) establishing stray current collection network; (5) adopting the drainage protection method, the cathodic protection method and other protective means to protect the corrosion objects; (6) setting the rail over-voltage protection devices (OVPD) [5–8]. Although these methods may reduce stray current and rail potential, the costs are too high while the effects are limited. So the stray current and rail potential issues still cause huge economic losses. The fundamental reason for the limited effects of these methods is that the running rails always act as the return path of traction current, and it's essential to propose a new structure of traction power supply system (TPSS) to solve the problems fundamentally.

In order to solve the above mentioned issues, the fourth-rail DC railway system has been used in practice [9, 10]. But it requires additional provision for the fourth rail, whereas the cost is high. The fourth-rail DC railway system needs to improve the train's design additionally, so it doesn't get a wide range of promotion. Reza Fotouhi [11] proposed a DC booster circuit to reduce stray current and rail potential in DC railways, by using DC booster circuit to transfer the traction current from the rail to the return line. This method requires additional provision of the return line and a number of the booster circuits, meanwhile each booster requires two bulky inductors and eleven switches. All switches are operating in the hard switching mode, and there is dead time interval between the switching operating modes. During the dead time interval, the traction current still goes through the rail like the existing TPSS (E-TPSS). Qunzhan Li [12] proposed a single-phase AC TPSS to replace E-TPSS for urban rail transit. With higher power supply voltage, the insulation level between the train and tunnels is higher. What's more, the train's traction drive system needs to be improved greatly with DC power supply changed to AC power supply.

Compared with these systems' problems in terms of power density, efficiency, cost, reliability and so on, Trillion Q. Zheng [13] proposed DC auto-transformer (DCAT) TPSS. DCAT-TPSS uses DCAT to transfer the traction current from the rail to the negative feeder, thus reduces stray current and rail potential fundamentally. DCAT-TPSS is verified through the mathematical analysis and simulation in this paper, by comparing with E-TPSS based on grounded scheme. The results show that DCAT-TPSS not only solves both stray current and rail potential issues, but also reduces the voltage drop and power loss of power supply lines.

## 2 Configuration and Principle of DCAT-TPSS

Figure 1 shows the general configuration of DCAT-TPSS, which adds the negative feeder and several DCATs compared with E-TPSS. Figure 2 shows the configuration of DCAT, which is comprised of two capacitors and one energy transfer module (ETM). The ETM is responsible for balancing the voltage across of

capacitors. The ETM may adopt the resonant cell (including the resonant capacitor and the resonant inductor) to transfer the energy, as shown in Fig. 2b, or the DC inductor, as shown in Fig. 2c, and the principles of ETM have been introduced in [13, 14]. Moreover, DCAT's terminals (i.e. HPT, MPT and LPT) are connected to the contact line (or the third rail), the rail and the negative feeder respectively.

In DCAT-TPSS, DCAT is used as a step-up converter in the substation side and a step-down converter in the train side, when the train runs under traction condition. Therefore, the voltage level of power supply lines increases, the voltage drop and power loss of power supply lines decreases, and the power supply distance of the substations can be further extended. What's more, the train's voltage level remain unchanged in DCAT-TPSS, which means the existing trains may be used in DCAT-TPSS directly without any improvement.

As shown in Fig. 1, substation1 and substation2 supply the energy to the train together, and by installing four DCATs, the rail can be divided into three sections: section I, section II and section III. Figure 3 shows the current distribution of DCAT-TPSS when the train is running on section II. No matter which section the train is running on, DCAT will transfer the total traction current from the rail to the

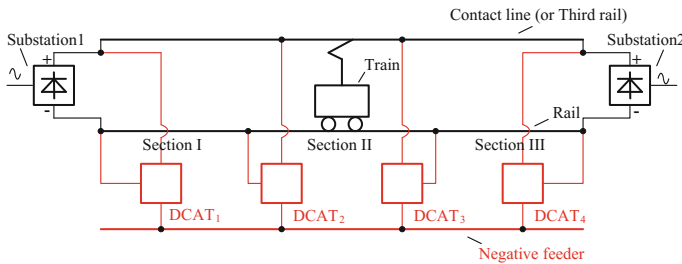


Fig. 1 General configuration of DCAT-TPSS

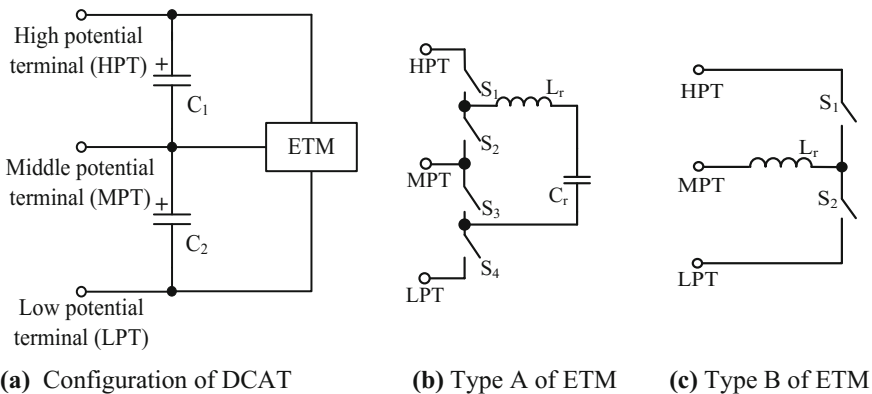
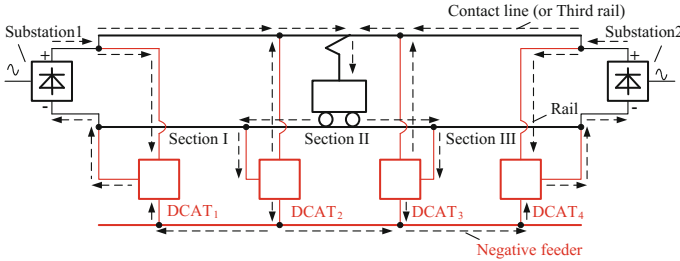


Fig. 2 Configuration of DCAT and ETM



**Fig. 3** The current distribution of DCAT-TPSS when the train is running on section II

negative feeder. Thus the traction current only exists in the section which the train is running on, and the current of the section which no train is running on is zero. So DCAT-TPSS may solve the problems of stray current and rail potential fundamentally.

### 3 Mathematical Analysis of DCAT-TPSS and E-TPSS

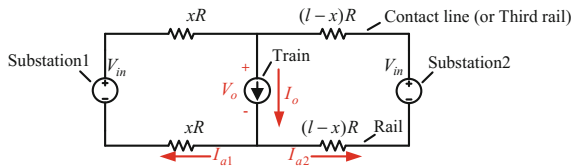
To compare DCAT-TPSS and E-TPSS, this paper will discuss rail potential, stray current, leakage charge, voltage drop and power loss of power supply lines based on grounded system (i.e. the negative terminal of the substations is grounded).

Figures 4 and 5 show the equivalent model of E-TPSS and DCAT-TPSS respectively. In these models, the substations are equivalent to voltage sources  $V_{in}$ , and the train is equivalent to current source  $I_o$ . The distance between the substations is  $l$ , and the distance between the train and the substation1 is  $x$ . The resistance per unit length of the rail, the contact line and the negative feeder is  $R$ . What's more, by installing  $N + 1$  DCATs, the rail of DCAT-TPSS can be divided into  $N$  sections, and the train runs on section  $N_1 + 1$  (i.e. the running section).

#### 3.1 Rail Potential

Based on the equivalent models of E-TPSS and DCAT-TPSS, the rail potential gets the maximum value  $V_{max}$  at position of the train, and the rail potential gets the

**Fig. 4** The equivalent model of E-TPSS



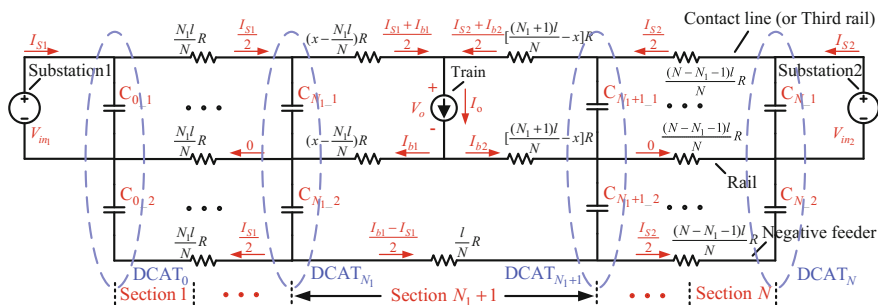


Fig. 5 The equivalent model of DCAT-TPSS

minimum value (i.e. 0) at position of the substations. From the equivalent models, the maximum rail potential value of E-TPSS and DCAT-TPSS can be described as

$$V_{E-TPSS_{max}} = \frac{lR I_o}{4} \tag{1}$$

$$V_{DCAT-TPSS_{max}} = \frac{lR I_o}{4N} \tag{2}$$

So the maximum rail potential ratio of DCAT-TPSS to E-TPSS is expressed as

$$\frac{V_{DCAT-TPSS_{max}}}{V_{E-TPSS_{max}}} = \frac{1}{N} \tag{3}$$

### 3.2 Stray Current

Because the rail potential causes the voltage difference between the rail and the ground, under the resistance  $R_G$  between the rail and the ground, the leakage current  $I_G$  will gather together continuously, and cause the stray current issue. From the equivalent models, the maximum stray current value of E-TPSS and DCAT-TPSS can be described as

$$I_{E-TPSS_{max}} = \frac{l^2 R I_o}{16 R_G} \tag{4}$$

$$I_{DCAT-TPSS_{max}} = \frac{l^2 R I_o}{16 N^2 R_G} \tag{5}$$

So the maximum stray current ratio of DCAT-TPSS to E-TPSS is expressed as

$$\frac{I_{DCAT-TPSS_{max}}}{I_{E-TPSS_{max}}} = \frac{1}{N^2} \tag{6}$$

### 3.3 Leakage Charge

According to the analysis of the stray current, the sum of the leakage currents equals to the sum of the maximum stray currents on the left and right sides of the train. For simplified analysis, it is assumed that the train runs from the substation1 to the substation2 at a constant speed  $v$ , and the sum of the leakage charges of E-TPSS and DCAT-TPSS can be calculated as

$$Q_{E-TPSS} = \int_0^{\frac{l}{v}} I_{G\_E-TPSS\_sum} dt = \frac{l^3 RI_o}{12vR_G} \quad (7)$$

$$Q_{DCAT-TPSS} = \sum_{N_1=0}^{N-1} \int_{\frac{N_1 l}{Nv}}^{\frac{(N_1+1)l}{Nv}} I_{G\_DCAT-TPSS\_sum} dt = \frac{l^3 RI_o}{12N^2 v R_G} \quad (8)$$

So the leakage charge ratio of DCAT-TPSS to E-TPSS is expressed as

$$\frac{Q_{DCAT-TPSS}}{Q_{E-TPSS}} = \frac{1}{N^2} \quad (9)$$

### 3.4 Voltage Drop and Power Loss of Power Supply Lines

Based on the equivalent models of E-TPSS and DCAT-TPSS, the average voltage drop and power loss of power supply lines can be expressed as

$$\Delta V_{E-TPSS\_avg} = \frac{1}{l} \int_0^l \Delta V_{E-TPSS} dx = \frac{lRI_o}{3} \quad (10)$$

$$\Delta P_{E-TPSS\_avg} = \frac{1}{l} \int_0^l \Delta P_{E-TPSS} dx = \frac{lRI_o^2}{3} \quad (11)$$

$$\Delta V_{DCAT-TPSS\_avg} = \frac{1}{N} \sum_{N_1=0}^{N-1} \left( \frac{N}{l} \int_{\frac{N_1 l}{N}}^{\frac{(N_1+1)l}{N}} \Delta V_{DCAT-TPSS} dx \right) = \frac{(N+3)lRI_o}{12N} \quad (12)$$

$$\Delta P_{DCAT-TPSS\_avg} = \frac{1}{N} \sum_{N_1=0}^{N-1} \left( \frac{N}{l} \int_{\frac{N_1 l}{N}}^{\frac{(N_1+1)l}{N}} \Delta P_{DCAT-TPSS} dx \right) = \frac{(N+3)lRI_o^2}{12N} \quad (13)$$

So the average voltage drop ratio and power loss ratio of DCAT-TPSS to E-TPSS are expressed as

$$\frac{\Delta V_{\text{DCAT-TPSS}_{\text{avg}}}}{\Delta V_{\text{E-TPSS}_{\text{avg}}}} = \frac{\Delta P_{\text{DCAT-TPSS}_{\text{avg}}}}{\Delta P_{\text{E-TPSS}_{\text{avg}}}} = \frac{N + 3}{4N} \tag{14}$$

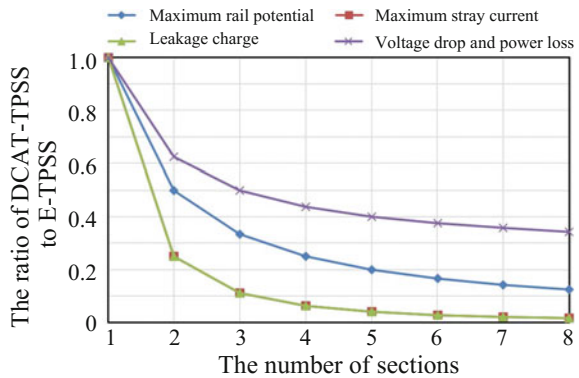
From the mathematical analysis of DCAT-TPSS and E-TPSS, DCAT-TPSS can solve the rail potential, stray current and leakage charge issues effectively compared with E-TPSS, and reduce the voltage drop and power loss of the power supply lines additionally, which means DCAT-TPSS can improve power distance and power efficiency of the substations.

Compared with E-TPSS, if the rail is divided into  $N$  sections in DCAT-TPSS, it can be concluded as: (1) the maximum rail potential ratio is  $1/N$ ; (2) the maximum stray current ratio is  $1/N^2$ ; (3) the leakage charge ratio is  $1/N^2$ ; (4) the average voltage drop ratio and power loss ratio are  $(N + 3)/4$ . As can be seen in Fig. 6, with increasing the number  $N$  of sections (i.e. add one to the number of DCATs), the effect of DCAT-TPSS will be better. With comprehensive consideration of the effect and the cost of DCAT-TPSS, the recommended number of sections is 3 to 5 under the different distance between the substations.

### 4 Simulation Results

In order to validate the above mathematical analysis, build DCAT-TPSS as shown in Fig. 1, and E-TPSS in Matlab software, which are based on grounded system. DCAT's EMT adopts the type A (i.e. the resonant cell), and the main parameters of DCAT-TPSS and E-TPSS are given in Table 1. To simplify the analysis, all the components are assumed ideal.

**Fig. 6** The ratio of DCAT-TPSS to E-TPSS

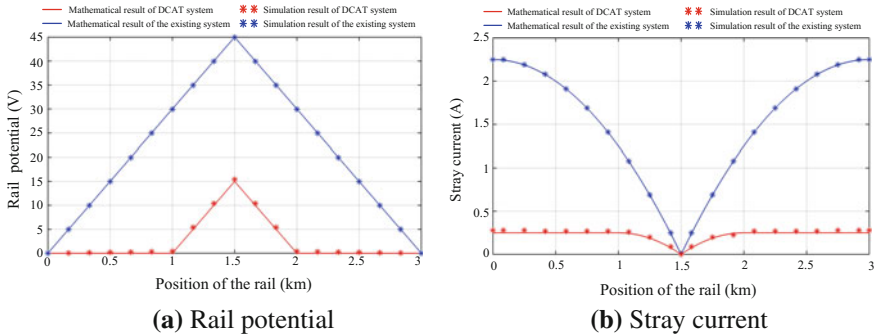


**Table 1** Simulation parameters of DCAT-TPSS and E-TPSS

	Parameters
$V_{in}$	750 V
$I_o$	2000 A
$R$	30 mΩ/km
$R_G$	15Ω km
$l$	3 km
$v$	120 km/h
The number of DCAT	4

Figure 7 shows the comparison about the rail potential and stray current, when the train is running on the midpoint of the rail. The rail potential at position of the train achieves the maximum value, and the stray current at position of the substations achieves the maximum value. Figure 8 shows the comparison about the sum of leakage currents, leakage charge, voltage drop and power loss, when the train runs from the substation1 to the substation2. The sum of leakage currents, the voltage drop and power loss achieve the maximum value when the train is running at midpoint of the rail, and the leakage charge achieves the maximum value when the train is running at right substation (i.e. the end of the travel).

The simulation results are consistent with the mathematical results, which proves the correctness of the mathematical analysis. The simulation results show that DCAT-TPSS can effectively solve the problems of rail potential and stray current, and reduce the voltage drop and power loss of the power supply lines.



**Fig. 7** Comparison when the train is running on the midpoint of the rail



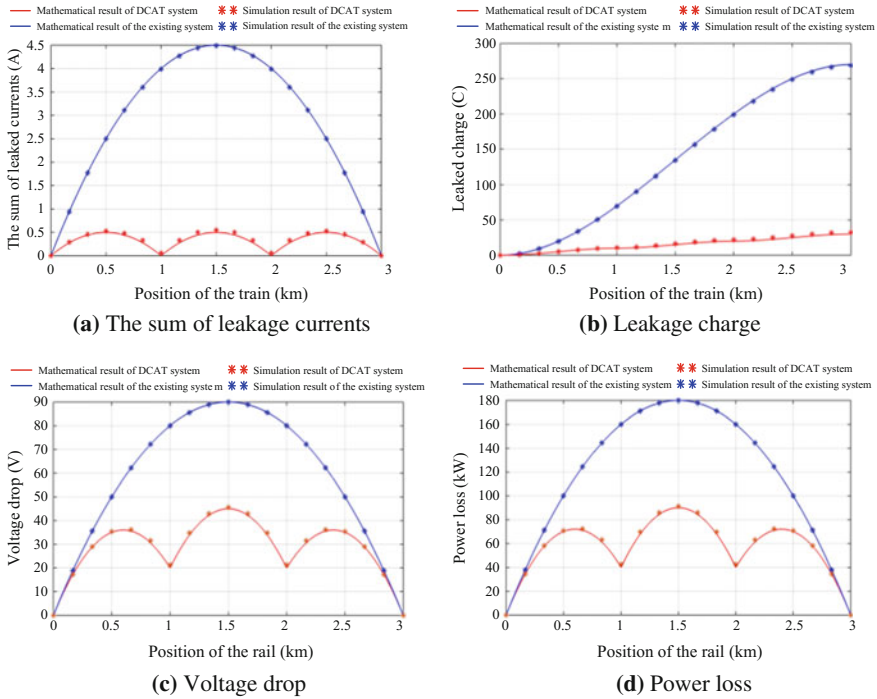


Fig. 8 Comparison when the train runs from the substation1 to the substation2

## 5 Conclusion

DCAT-TPSS has been described and demonstrated in this paper. Mathematical analysis and simulation results show that, DCAT-TPSS may solve rail potential and stray current issues by transferring the traction current from the rail to the negative feeder, and reduce the voltage drop and power loss additionally with the voltage level of power supply lines doubling, which effectively proves that DCAT-TPSS has a promising application prospect in DC railways.

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