TELKOMNIKA, Vol.11, No.2, February 2013, pp. 848~854
ISSN: 2302-4046

Power Flow Calculation for Traction Networks under Regenerative Braking Condition Based on Locomotive-Traction Network Coupling

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Abstract

The regenerative braking technology is widely applied in high-speed electric multiple units (EMUs). And the voltage rise problem at end of the traction network would be caused by regenerative braking attracts more and more attention. The arm of this paper is to analyze the power flow calculation for EMUs under regenerative braking condition. Power flow calculation was done for two different EMU operation conditions by using a "locomotive-traction network" coupling model. In this model, a constant power load model on an all-parallel AT network multi-conductor chain circuit model is considerable. The simulation analysis shows that the iterative calculation method used in the present study is characterized by fast convergence and high accuracy, and is suitable to power flow calculation for traction networks under the braking condition and traction condition. It can be used to analyze voltage distribution, and the impact of traction load on power quality of the public power grid, etc.

Keywords*: Regenerative braking; Power flow calculation; All-parallel AT network;Locomotive-traction network coupling; Iterative calculation method*

1. Introduction

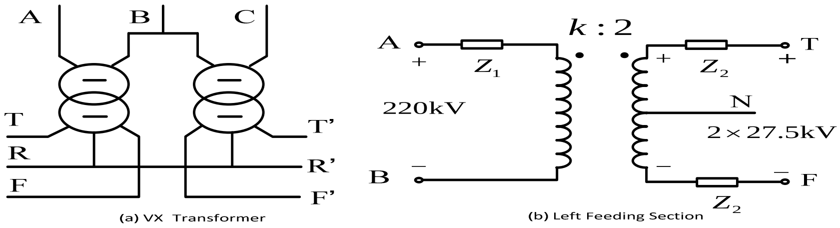
In the process of fast development of China's high-speed railways, overcurrent of electrification equipment and voltage loss at the extremity of the traction network become more and more serious due to fast promotion of power demand, speed, and operation density of high-speed trains. Nevertheless, regenerative braking technology that is widely applied in EMUs provides necessary braking force for EMUs and at the same time the regenerative energy returns to traction transformers via the overhead contact system (OCS). Regenerative energy circulates in two ways: one is to be supplied to other locomotives of the same feeding section and the other is to return to the power grid or be supplied to stations or depots. Now, voltage rise at the traction network end caused by regenerative braking attracts more and more attention, and new problems on power flow calculation arise accordingly [2-4]. It is of great significance to study flow characteristics of regenerative braking energy under different operating conditions (different number, power and location of locomotives) so as to avoid overvoltage and to develop reasonable energy storage strategy.

In operation of high-speed railways, voltage of traction networks varies to operating condition and locomotive location. For locomotive load models, constant electrical quantities (constant power, constant current, and constant impedance, etc.) are usually used for modeling[5-8]. As running locomotives are deemed as static load in these modeling methods, the corresponding description of load of high-speed trains is not exact. For example, in Reference [5], the train was deemed as a constant-impedance model, which means that the train is a load that varies with the change of network voltage. Such a train model cannot meet the actual demands. In Reference [6], the train was deemed as a constant current source, which means that the injection current to the traction network from the train is a constant. In References [7-10], the train was deemed as a constant power source, and the equivalent injection current source was worked out through iteration of the train network voltage. The train is a power consumption element (impedance) but a feeding current source, and its impedance affects the topological structure of the system.

Received August 17, 2012; Revised December 30, 2012; Accepted January 14, 2013

In the paper, the traction network chain model and locomotive integrated model were further optimized based on Reference [7]. Considering different network-side current conditions and traction conditions during operation of the regenerative braking of high-speed trains, we obtained the voltage distribution through the whole traction network by iteration of locomotives under different conditions and powers. Our emphasis was placed on voltage rise caused by locomotives under regenerative braking condition and energy flow rule under various conditions.

2. V/X Traction Transformer Model



T—OCS; R—rail; F—feeder; N—neutral point

Figure.1 V/X Traction Transformer Circuit Model

Now, Vv transformers are mainly used as traction transformers for high-speed railways in China. Vv connection is such that two single-phase transformers in the traction substation are respectively connected to two different line voltage, and one phase is used as the common terminal. Vv-connection transformers are widely used due to its capacity utilization of 100%, simple main connection, less devices required, and high economical efficiency. In case of integration with AT feeding mode, V/X connection is used for traction transformers. Namely, a secondary third winding is used. The connection schematic diagram is shown in Figure 1. It can be seen from Figure 1 (b) that the node admittance matrix [11] of V/X-connection transformers is as follows:

$$\begin{bmatrix} I_A \\ I_B \\ I_T \\ I_F \\ I_R \end{bmatrix} = \frac{1}{4Z_t}\begin{bmatrix} 4 & -4 & -2k & 2k & 0 \\ -4 & 4 & 2k & -2k & 0 \\ -2k & 2k & k^2+m & -k^2+m & -2m \\ 2k & -2k & -k^2+m & k^2+m & -2m \\ 0 & 0 & -2m & -2m & 4m \end{bmatrix}\begin{bmatrix} U_A \\ U_B \\ U_T \\ U_F \\ U_R \end{bmatrix} \quad (1)$$

where, $m=\frac{2Z_t}{Z_2}$, $Z_g=\frac{1}{Z_2}$, $Z_t=Z_1+\frac{k^2Z_2}{2}$, Z_1, and Z_2 is the equivalent impedance of the traction transformer primary and secondary windings respectively; k is the ratio of high-voltage side voltage to traction side voltage, k=220kV:27.5kV.

3. Traction Network Chain Model

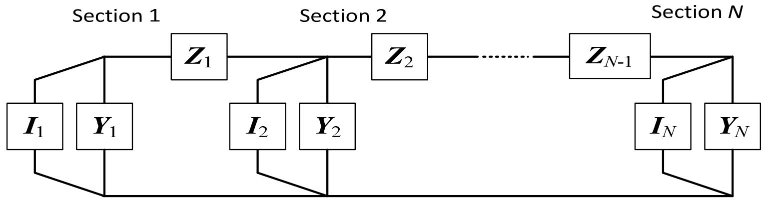


Figure 2. Traction Network Chain Circuit Model

In Reference [7], the model was established based on the chain circuit theory by dividing the traction network into sections with a length of 1 km. The exponent number of the node admittance matrix obtained by this model is high. Moreover, only the electrical quantities of unit distance can be investigated, so its smoothness is poor. In the present study, the AT substation, section post, and locomotive location were deemed as sections, the impedance matrix and admittance matrix of traction network were calculated according to the distance between two neighboring sections. Finally, the equivalent chain circuit model [10] as shown in Figure 2 was established.

The node admittance matrix as shown in formula (2) was obtained according to Figure 2.

$$\boldsymbol{Y}=\begin{bmatrix} \boldsymbol{Y}_1+\boldsymbol{Z}_1^{-1} & -\boldsymbol{Z}_1^{-1} & & & \\ -\boldsymbol{Z}_1^{-1} & \boldsymbol{Z}_1^{-1}+\boldsymbol{Y}_2+\boldsymbol{Z}_2^{-1} & & & \\ & \mathrm{O} & \mathrm{O} & \mathrm{O} & \\ & & & \boldsymbol{Z}_{N-2}^{-1}+\boldsymbol{Y}_{N-1}+\boldsymbol{Z}_{N-1}^{-1} & -\boldsymbol{Z}_{N-1}^{-1} \\ & & & -\boldsymbol{Z}_{N-1}^{-1} & \boldsymbol{Z}_{N-1}^{-1}+\boldsymbol{Y}_N \end{bmatrix} \tag{2}$$

4. Train Load Model

In the present study, a constant power model was used for high-speed trains, which means that during normal operation of a train, no matter it is at any location in the traction network, the power keeps constant. However, in case of different condition and location of the train, the receiving voltage and current of the train and topological structure of the traction feeding system will change, which results in change of the equivalent circuit model of EMUs accordingly.

The equivalent current of the train running at a constant power can be obtained according to (3):

$$I_{\text{train}} = (P + jQ) / U_{\text{train}} \tag{3}$$

5. Power Flow Calculation

In China, the power system connected to traction substations of high-speed railways is usually three-phase 220 kV power grid and the voltage is transformed into two-phase 55 kV or 2×27.5kV via VX-connection transformers (or single-phase transformers) for use by two-section traction networks. Usually, one AT substation with a transformation ratio of 1:1 is set every 12.5 km. In the AT substation, + 27.5kV is connected to the contact line; -27.5kV is connected to the feeder; the center is connection to the rail.

The all-parallel AT network power flow is mainly based on two conditions: 1) the AT substation evenly allocates the rail current to the up/down feeder and contact line; 2) the rail current distribution of the locomotive in AT section is in inverse proportion to the its distance to AT.

To exhibit characteristics of locomotive-traction network coupling, it is necessary to perform iterative calculation for the current at the train end. Namely, we should perform iterative refinement for I_{train} by using (3). The iterative calculation was done according to the following basic steps:

1) Divide the traction network into N sections according to train location and speed, and calculate the corresponding traction network node admittance matrix according to the distance between two sections and conductor spatial distribution.

2) Establish model for the traction transformer and traction network, etc. to form the system admittance matrix and develop the node voltage equation as formula (9). Set the initial voltage value at each node of the traction network as the rated voltage.

$$\boldsymbol{U} = \boldsymbol{Y}^{-1} \cdot \boldsymbol{I} \tag{4}$$

where, $\boldsymbol{U}$ and $\boldsymbol{I}$ are the node voltage matrix and injection current matrix respectively. The injection current, I_{train} of high-speed trains in regenerative condition is contrary to I_{train} of high-speed trains in traction condition.

3) According to the voltage at the point where the train is located in the traction network and the running speed of the train, calculate the injection/receive current $I_{\text{train}}^{(k)}$ of the train at such speed and voltage according to (4). In $I_{\text{train}}^{(k)}$, k is iteration times. Calculate the train current according to the train load model. Then update the current vector $\boldsymbol{I}$, to solve (4) so as to work out the new voltage vector $\boldsymbol{U}^{(1)}$ at each node.

4) Set the iterative accuracy $\varepsilon = \left\| I_{\text{train}}^{(k)} - I_{\text{train}}^{(k-1)} \right\|$. If ε is less than the given error, stop the iteration. If ε is not less than the given error, return to step 3) to update the train current until the iterative accuracy is met.

6. Case analysis and Simulation

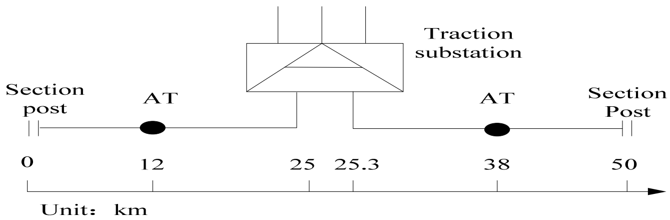


Figure 3. Traction Substation Power Supply Area

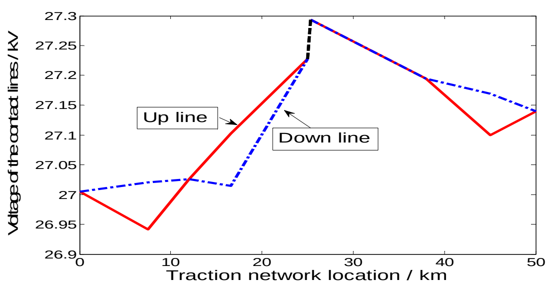


Figure 4. Voltage Distribution of Contact Line

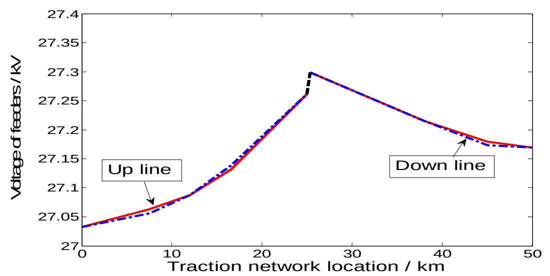


Figure 5. Voltage Distribution of Feeder

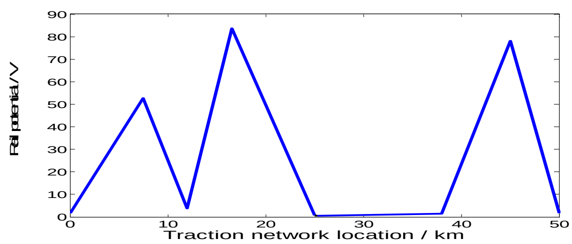


Figure. 6 Voltage distribution of rail

According to Figure 3, suppose that both the right and left feeding sections of a traction network are 25 km long, each feeding section has one 13 km-long AT section and one 12 km AT section, and a 300m neutral section is set at the outlet of the traction substation. In neutral section, the contact line and feeder of both the right and left feeding sections are fully insulated but rails are connected and grounded. The system parameters are as follows: the 16-car CRH2 EMU is selected for the locomotive with a rated power of 9.6 MW and power factor of 0.98 (lagging); the power system is of 220 kV power supply with a short-circuit capacity of 4 GW; the rated capacity of traction transformer is 63 MVA and short-circuit impedance ratio is 15%; the

AT leakage impedance is 0.1+j0.45 Ω, grounding resistance is 0.5Ω, and rail to ground leakage impedance resistance is 100 Ω.km[7].

Supposing one locomotive runs under regenerative braking condition on the up line and one locomotive runs under regenerative braking condition on the down line, and regenerative braking energy fully returns to the traction substation, which can be stored with energy storage devices or sent to the traction network, the OCS voltage will significantly rise and thus negatively affect the insulation on the top of the locomotive. Supposing one train runs with a regenerative power of 6 MW at 7.5 km of the up line and one train runs with a traction power of 9.6 MW at 16.6 km of the down line, and the third train runs with a traction power of 8.9 MW at 45 km of the up line their power factors are 0.95, 0.98 and 0.99, respectively. And the voltage distribution of the traction network in this case is shown in Figures 4 until 6. It can be seen that:

1) In the left feeding section, the traction network voltage at the point where the two locomotives under regenerative braking condition are located is high and the maximum voltage nearly reaches 28kV. With increase of regenerative braking power, the voltage may become higher. In the right feeding section where there is no train running, change of the contact line voltage and feeder voltage is small, and the voltage rises slightly at the end of the traction network;

2) As the right and left feeding sections are electrically isolated at the phase splitting point, the contact line voltage and feeder voltage of the two feeding sections are not continuous. The contact line voltage amplitude and feeder voltage amplitude of the right feeding section are equal;

3) As the feeder is not in direct contact with the train, its up line and down line exhibit good symmetry, and voltage change is small.

4) As the AT neutral point is grounded, the rail voltage at AT is the lowest, and it is related to locomotive power in the same one AT section. The greater the power is, the higher the rail voltage amplitude will be.

7. Conclusion

The iterative calculation by establishing a power analysis model for high-speed EMUs under traction condition and regenerative braking condition and deeming the EMUs as a constant power source shows that this iterative calculation method has good convergence and so is applicable to power flow calculation for traction feeding systems in case of locomotive-traction network coupling. To investigate the traction network voltage rise caused by regenerative braking and the energy flow, in the present study, the following conclusions were made based on comparison between two different conditions.

1) If the impact of the system impedance is not considered, the voltage loss caused by one locomotive under traction condition is equal to the voltage rise caused by the same locomotive at the same power under regenerative braking condition;

2) The locomotive running under regenerative braking condition inevitably results in voltage rise of the traction network at the point where it is located. At the same time, the voltage of the up contact line and down contact line is closely related to the locomotive condition. The up feeder and down feeder exhibit good symmetry, and the voltage is slightly affected by the locomotive operating condition. The rail voltage is closely related to AT grounding network resistance, and it reaches the minimum at AT location. In the same one AT section, the rail voltage is related to the locomotive power. The greater the locomotive power is, the higher the rail voltage will be.

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