



# Low-Frequency Oscillation Research of Sichuan-Tibet Railway Under Bilateral Power Supply for Mixed Passenger and Freight Locomotives Operation

Xiangyu Meng<sup>1</sup>(✉), Wen Xia<sup>1</sup>, Yunchuan Deng<sup>2</sup>, and Zhigang Liu<sup>1</sup>

<sup>1</sup> School of Electrical Engineering, Southwest Jiaotong University, Chengdu 611756, Sichuan Province, China

<sup>2</sup> China Railway Eryuan Engineering Group Co., Ltd., Chengdu 610031, Sichuan Province, China

**Abstract.** The Sichuan-Tibet railway contains long ramp. To ensure the uninterrupted power supply of the locomotives on the long ramp, the number of phase breaks is reduced. However, this will result that multiple locomotives operate together under the same power supply section and may further create unexpected low-frequency oscillation (LFO) in the Locomotive-network (L-N) system. Previous researches have established the L-N system model and analyzed the mechanism of LFO, but lacked the evaluation of the maximum operable locomotive number under the traction network. In this paper, according to the traction power supply mode and the locomotive in the Sichuan-Tibet railway, the maximum operable locomotive number to ensure the system stability is analyzed. It is found that under the same network-side parameters, the maximum operable locomotive numbers of the freight locomotives are higher than passenger locomotives. Finally, the simulation results validate the correctness of the theoretical results.

**Keywords:** Sichuan-Tibet railway · Low-frequency oscillation · Passenger and freight locomotives

## 1 Introduction

The engineering environment of the Sichuan-Tibet railway is extremely complicated, which passes through seven rivers and eight mountains with dramatically fluctuating topography. The highest steep slope is 30‰ and the longest ramp sections are more than 300 km, which is unavoidable to set phase break on the long ramp. Therefore, to ensure the locomotives can be continuously powered on the long ramp, the number of the phase break is reduced, which leads interconnection of multiple power supply arms without insulation partition [1]. Furthermore, multiple locomotives may interact with the traction network and then create unexpected LFO in the L-N system. In addition, the mixed operation of passenger (CRH380AL) and freight (HXD2) locomotives are used

in the Sichuan-Tibet Railway, which may introduce new dynamic interaction between different types of locomotives.

Previous theoretical researches on LFO have mainly focused on establishing the detailed L-N system model. The decoupled small-signal impedance model of CRH5 EMU in  $dq$ -axis has been established in [2], and the influence of traction network and control parameters on the L-N coupling system stability has been analyzed in [3]. However, the actual traction power supply mode was not considered in the previous research. The influence of mixed operating passenger and freight locomotives on high-frequency system stability has been analyzed in [4]. Nevertheless, system low-frequency stability under the mixed operation mode was not analyzed.

In view of the above problems, according to the actual operation requirements in the Sichuan-Tibet railway, this paper takes mixed operating CRH380AL and HXD2 locomotives to analyze the LFO under the bilateral power supply mode in the Sichuan-Tibet railway. The small-signal impedance model of the two locomotives in  $dq$ -axis are established firstly. The equivalent network-side impedance model, including external traction power source, single-phase traction transformer, and all-parallel direct power supply traction network, are calculated based on the actual parameters. Then, based on the dominant pole of the L-N system minimum loop gain and short circuit ratio (SCR), the relationship between the maximum operable locomotives number and the minimum stable SCR in the Sichuan-Tibet railway are analyzed. The results can provide design references and suggestions for the actual operation of the Sichuan-Tibet railway.

This paper is structured as follows. Section 2 introduces the background of the Sichuan-Tibet railway traction power supply system. Then, the coupling L-N system impedance models in the Sichuan-Tibet railway are established in Sect. 3. Section 4 analyzes the low-frequency stability in the bilateral power supply system of the Sichuan-Tibet railway under mixed operating passenger and freight locomotives. The stability analysis results are verified under multiple operation cases by Matlab/Simulation in Sect. 5. Section 6 summarizes the conclusions.

## 2 Background

Traditional electrified railway power supply system has widely adopted direct power supply under unilateral power supply mode. The double-line traction network adopted the parallel connection of the up and down lines at the end of the power supply arm. In this kind of power supply mode, an insulation partition is set between the two traction substations to achieve phase break insulation. The traditional power supply system has two main disadvantages. First, the up (down) lines are formed as power island partition under partial parallel and unilateral power supply mode. Therefore, the locomotive cannot obtain traction power through another traction substation or down (up) lines when the traction power supply is fault, resulting in poor reliability. In addition, due to the phase break in the traction substation, the power supply of  $\alpha$  and  $\beta$  arms are insulated and divided, resulting in low utilization of the traction power supply where the different number of locomotives are accessed into different arms.

The Ya'an-Nyingchi section of the Sichuan-Tibet Railway is located on long ramp. The external power supply conditions of the traction power supply system are fragile,

lacking the high-voltage power network. Therefore, to ensure the uninterrupted operation of locomotives and improve the power supply reliability, it is necessary to reduce the phase break along the railway and break the power island between the power supply arms in the traditional traction power supply system.

To solve the above problems, a suitable traction power supply system structure should be designed for the Sichuan-Tibet Railway, considering the following aspects from “external power source-traction substation-traction network”. For external power sources, the high-voltage side (220 kV) of traction substations are connected to each other in the same busbar to achieve the multi-substation interconnection. For traction substations, single-phase traction transformers are applied to eliminate the phase break in the traction substation to accomplish the interconnection of the power supply arms on the left and right sides. Then, by adopting bilateral power supply mode, the phase break between the two traction substations is eliminated. For the traction network, the full parallel power supply mode is adopted to achieve the interconnection between the up and down lines. Through these design structures from “external power source- traction substation-traction network”, the electrical interconnection from “source-network-locomotive” is realized, which significantly improves the reliability of the traction power supply system. In addition, it can efficiently utilize traction power and braking energy among the different locomotives, improving the energy utilization rate of the entire traction power supply system. Finally, since the single-phase traction transformer and bilateral power supply mode are adopted, the phase breaks in the traction power supply system are greatly reduced, and the uninterrupted power supply of the locomotive is guaranteed in the long ramp.

However, this traction power supply system structure will result that multiple locomotives operate together under the same power supply section and may further create unexpected LFO in the L-N system. The maximum operable locomotives should be evaluated and analyzed under different traction network parameters to avoid LFO phenomenon before designing the Sichuan-Tibet railway.

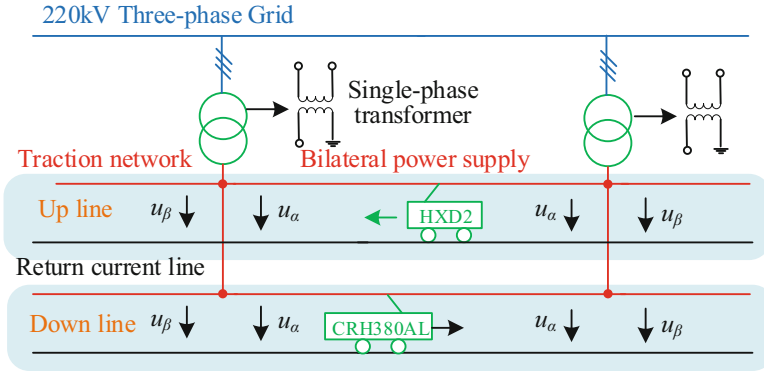
### 3 Modeling of Locomotive-Network System in Sichuan-Tibet Railway

#### 3.1 Network-Side Model

As shown in Fig. 1, the structure of Sichuan-Tibet Railway contains 220 kV outside three-phase network, single-phase traction transformer in the traction substation and a traction power supply arm in  $\alpha$  and  $\beta$  phase.

In the three-phase grid, the short-circuit capacity  $S_{SC}$ , the ratio of the equivalent resistance and reactance  $K = 10.5$ , and the rated voltage  $U_G = 220$  kV. The secondary side rated voltage in traction transformer  $U_B = 27.5$  kV. The relationship between these variables are shown in (1).

$$R_G = \frac{1}{K} \times \frac{U_G^2}{S_{SC}} \cdot \left(\frac{U_B}{U_G}\right)^2 \quad X_G = \frac{U_G^2}{S_{SC}} \cdot \left(\frac{U_B}{U_G}\right)^2 \quad (1)$$



**Fig. 1.** Schematic diagram of the Sichuan-Tibet railway under the bilateral power supply.

In the Sichuan-Tibet Railway, the single-phase transformer is adopted, and the transformer impedance converted to a low-voltage side can be expressed in (2).

$$R_T = \frac{P_k}{1000} \times \frac{U_{1N}^2}{S_T^2} \cdot \left(\frac{U_B}{U_G}\right)^2 \quad X_T = \frac{U_k^0/0}{100} \times \frac{U_{1N}^2}{S_T} \cdot \left(\frac{U_B}{U_G}\right)^2 \quad (2)$$

The full-parallel direct power supply with overhead wires is adopted in the Sichuan-Tibet railway traction network. The equivalent impedance of the traction network can be simplified as  $r_i \angle \varphi = 0.32 \angle 73^\circ$ .

### 3.2 HXD2 and CRH380AL Locomotive Model

The line-side rectifier is an important part of determining the input-impedance characteristic of the locomotive. To evaluate the influence the locomotive on the system stability, the small-signal impedance model of HXD2 and CRH380AL locomotives are established. To simplify the analysis, the equivalent load, including traction inverter, traction motors, and auxiliary converters, are modeled as a constant impedance, where its value refers to the actual operating power of the locomotive.

Figure 2 is a system structure and control diagram of the simplified traction drive unit in the locomotive.  $R_s$  and  $L_s$  denote the equivalent leakage resistance and inductance of the on-board transformer.  $u_{ab}$  is the rectifier ac-side voltage.  $v_s$  is the ideal traction network voltage source.  $C_{dc}$  is the dc-side support capacitance and  $u_{dc}$  is the dc-side voltage.

As shown in Fig. 3, the line-side rectifier adopts transient current control, which consists of the direct voltage control (DVC) loop, alter current control loop (ACC), phase-locked loop (PLL) and double polar pulse width modulation (PWM). According to Fig. 3, the small-signal impedance of the traction drive unit can be derived as follows [5].

$$Z_i = (G_{isvs} + G_{isiref}H_{dvc})^{-1}(I - G_{isiref}H_{dci}) \quad (3)$$

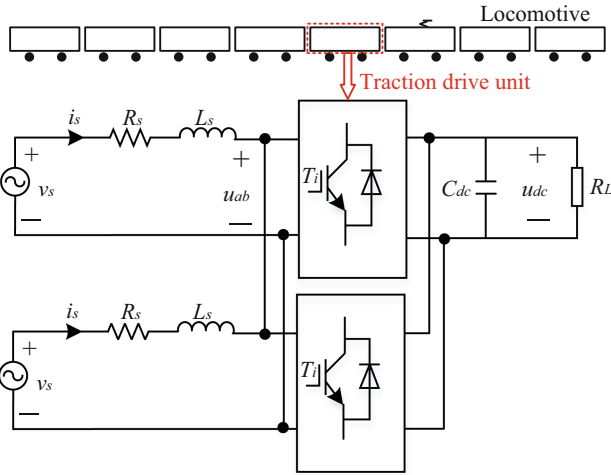


Fig. 2. Structure diagram of the simplified traction drive unit.

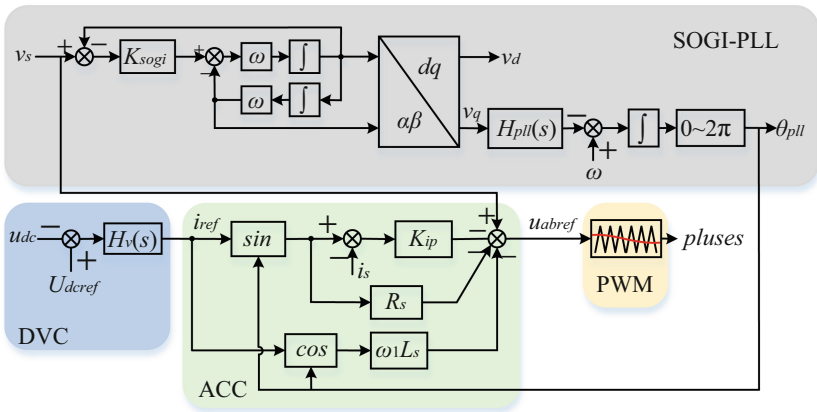


Fig. 3. Control block diagram in traction rectifier.

The total input-impedance of CRH380AL can be converted to the high-voltage side of the on-board transformer as follows [6, 7]

$$Z_{in\_1} = \frac{Z_i}{k_{CRH380}^2} \tag{4}$$

where  $k_{CRH380} = 15.07$  is the transformer ratio in CRH380AL.

Since the CRH380AL contains seven traction drive units, the total equivalent impedance can be expressed as follows [6, 7].

$$Z_{inCRH380} = \frac{1}{7} Z_{in\_1} \tag{5}$$

Similarly, the total equivalent impedance of HXD2 can be expressed as follows

$$Z_{inHXD2} = \frac{Z_i}{6k_{HXD2}^2} \quad (6)$$

where the  $k_{HXD2} = 26.31$  is the transformer ratio in HXD2.

## 4 Stability Analysis Under Different SCR

If the traction power supply is strong enough, the network-side impedance is zero, any variation of the locomotives will not introduce the LFO phenomenon. However, the actual traction power supply in the Sichuan-Tibet railway is weak. Besides, since the single-phase transformer and bilateral power supply mode are adopted, the phase breaks in the traction power supply system are reduced. Therefore, multiple power supply arms are interconnected in the same power supply section, which may result in interaction between multiple locomotives. Under the weak traction power supply environment, with the number of locomotives increasing, the LFO phenomenon will happen [5].

To analyze the critical operable number of locomotives to prevent LFO phenomenon in the Sichuan-Tibet railway under different traction network parameters, the concept of SCR which has used to analyze the strength of traction power supply is adopted. The higher SCR of the traction power supply. It should be noted that when the damping ratio corresponding to the dominant pole of the L-N system is greater than 0.01 [5], the system can ensure low-frequency stability. The definition of SCR is shown as follows,

$$SCR = \frac{27.5^2}{31.5 \times 3X_O} \quad (7)$$

where the voltage reference value in the traction network is 27.5 kV, the rated power of the single-phase traction transformer is 31.5 MVA.

The relationship of minimum stable SCR and maximum operable locomotives are analyzed in Fig. 4. The blue line refers to the CRH380AL locomotives, and the orange line refers to the HXD2 locomotives. With the higher SCR, the maximum operable locomotives are increasing. Besides, Fig. 4 shows that, in the same SCR, the slope of CRH380AL and HXD2 are different, which means different types of the locomotive have different effects on system stability. Compared to the CRH380AL locomotive, the slope of the HXD2 locomotive is lower. Therefore, the HXD2 has a better stability performance in the traction network. When the SCR is set to 2 to prevent LFO phenomenon in the system, the maximum operable HXD2 is 13, but the CRH380AL is 5.

## 5 Simulation Verification

To verify the stability analysis results above, the CRH380AL and HXD2 simulation models are built in Matlab/Simulink. The traction network is simplified into the RL circuits with an ideal voltage source.

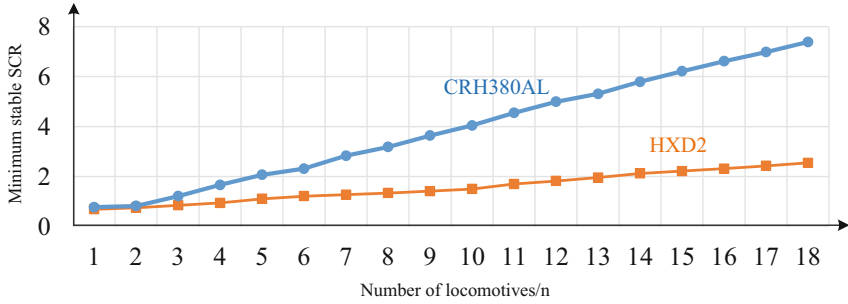


Fig. 4. Relationship between SCR and the maximum operable locomotives number

### 5.1 Influence of Single Locomotive on System Stability

When a CRH380AL accesses to the traction network, according to Fig. 4, the minimum stable SCR is 0.772, which is equivalent to the total traction network reactance  $X_o = 10.36 \Omega$ , and the value of network-side reactance  $L_o = 33 \text{ mH}$ . Therefore, in the simulation, when the network-side equivalent resistance  $R_o$  is set to  $3.6 \Omega$  and the network-side equivalent reactance  $L_o$  is set to  $37 \text{ mH}$ , the current and voltage waveforms in the high-voltage side of the on-board transformer are shown in Fig. 5. It can be seen in Fig. 5 that the system has a  $4.5 \text{ Hz}$  low-frequency oscillation frequency.

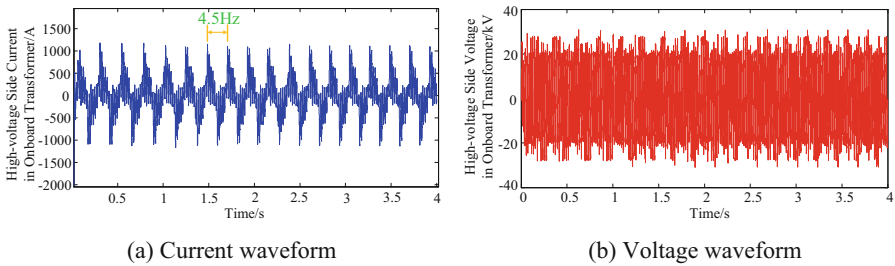
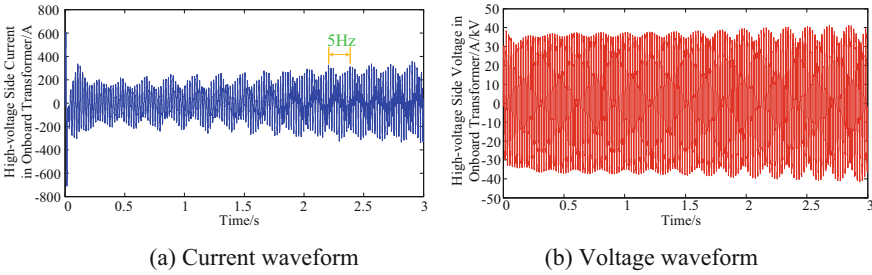


Fig. 5. Waveforms in on-board transformer when  $L_o = 37 \text{ mH}$  and single CRH380AL locomotive is accessed.

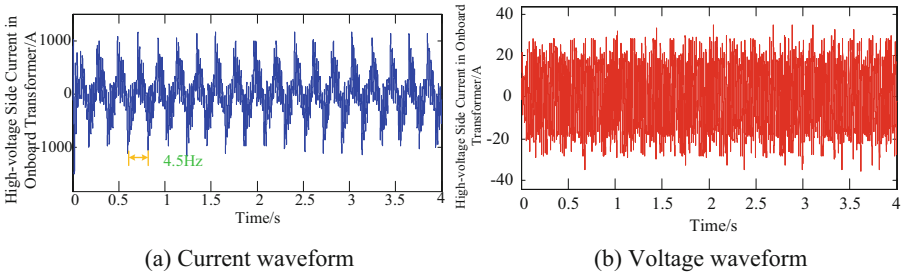
Similarly, when a single HXD2 is accessed to the traction network, according to Fig. 5, the minimum stable SCR is 0.688, which is equivalent to the total network-side reactance  $X_o = 11.62 \Omega$  and the corresponding  $L_o = 37 \text{ mH}$ . Therefore, when the network-side equivalent resistance  $R_o = 3.6 \Omega$  and reactance  $L_o = 37.1 \text{ mH}$ , the current and voltage waveforms in the high-voltage side of the on-board transformer are shown in Fig. 6. It can be seen in Fig. 6 that the system has a  $5 \text{ Hz}$  low-frequency oscillation frequency.



**Fig. 6.** Current and voltage waveforms on on-board transformer when  $L_o = 37.1$  mH and single HXD2 locomotive is accessed.

**5.2 Influence of Multiple Locomotives on System Stability**

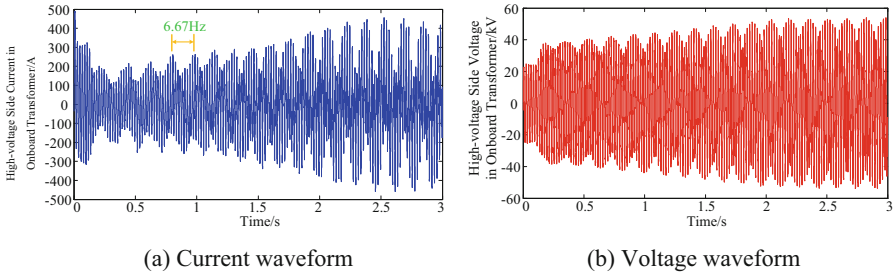
When five CRH380ALs are accessed in the traction network under the same power supply section, according to Fig. 7, the minimum stable SCR in the case is 2.07, which is equivalent to the total traction network reactance  $X_o = 3.86 \Omega$ , and the reactance  $L_o$  is 12.3 mH. Therefore, when the network-side equivalent resistance  $R_o$  is set to 1.1  $\Omega$  and the network-side equivalent reactance  $L_o = 12.4$  mH, the current and voltage waveforms in the high-voltage side of the on-board transformer are shown in Fig. 7. It can be seen in Fig. 7 that the system has a low-frequency oscillation of 4.5 Hz in the case.



**Fig. 7.** Current and voltage waveforms on on-board transformer when  $L_o = 12.4$  mH and five CRH380AL locomotives are accessed.

Similarly, when five HXD2 locomotives are accessed into the network, according to Fig. 8, the minimum stable SCR in the case is 1.107, which is equivalent to network reactance  $X_o = 7.22 \Omega$ , and the network-side reactance  $L_o = 23$  mH. Therefore, in the simulation, when the network-side equivalent resistance  $R_o$  is set to 2  $\Omega$  and the network-side equivalent reactance  $L_o$  is set to 23.1 mH, the current and voltage waveforms of the high-voltage side of the on-board transformer are shown in Fig. 8. It can be seen from Fig. 8 that a low-frequency oscillation of 6.67 Hz occurred in the system in the case.





**Fig. 8.** Current and voltage waveforms on on-board transformer when  $L_o = 23.1$  mH and five HXD2 locomotives are accessed.

## 6 Conclusion

In this paper, the low frequency stability problem is analyzed in the Sichuan-Tibet railway under bilateral power supply system for the mixed passenger and freight locomotives operation. The small-signal impedance model of the HXD2 and CRH380AL locomotives are established in the  $dq$  domain firstly. Then, the traction network impedance model, including the external power source, traction transformer, and traction network, are built according to the actual traction network structure in the Sichuan-Tibet railway. Then, the relationship between the minimum stable SCR and maximum operable locomotives number is analyzed in detail based on the critical dominant pole. It is found that under the same network-side parameters, the maximum operable locomotives number of the freight locomotives are higher than passenger locomotives, which can be utilized to design the traction power supply system parameters. Finally, the influence of different numbers and types of locomotives are analyzed to verify the correctness of low-frequency stability analysis results.

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