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Study on Low Frequency Voltage Fluctuation Considering Different Running-Vehicle Numbers in Electrical Railway

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***Abstract*—Low frequency voltage fluctuation (LFVF) have occurred frequently in electrical vehicle-grid traction system (VGTS) in China recently. The phenomenon can result in serious voltage distortions, system instabilities, even bring about electrical locomotive traction blockades. To address this issue, the LFVF stability analysis of VGTS is carried out in depth in this paper. First, the mathematical descriptions of VGTS are deduced based on the equivalent AT traction network model and the actual HX_D2B locomotive load model. Second, applying with the electrical parameters of Xu-zhou VGTS in China, the system stability based on Nyquist stability criteria is studied. Also, test results using the built VGTS model are compared to the real data, acquired from northern substation of Xu-Zhou in China, to verify the validity of mathematical VGTS descriptions and stability analysis respectively. The comparison results show that the conclusions of system description and stability can be useful for determining LFVF problem in electrical VGTS.**

***Index Terms*—Low frequency voltage fluctuation (LFVF), vehicle-grid traction system (VGTS), traction supply network, electrical locomotive, test experiment.**

I. Introduction

IN recent years, the rapid development of China's electric railway draws lots of attention all over the world. Specially, by the end of 2016 [1], with several new high-speed railway lines were put into operation, the overall mileage has hit to 22 thousand kilometers in China.

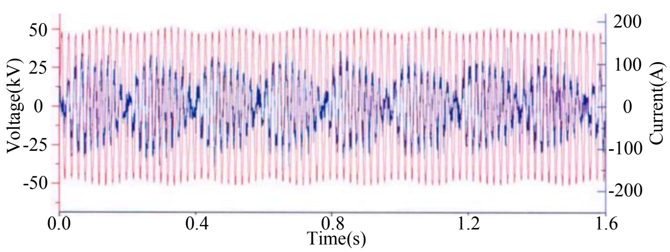

Fig. 1. Measured waveforms of low frequency voltage fluctuation (LFVF) in Xu-Zhou north substation.

Due to the high-density operation of electric locomotives some voltage distortions problems appeared. Among these problems, low frequency voltage fluctuation (LFVF) has occurred several times in electrical vehicle-grid traction system (VGTS) in China recently [2]. For example, during the operation of the intercity rail from Beijing to Tianjin in August, 2008, LFVF led to the frequent breakdown protection of main circuit breaker in the electric multiple units. Moreover, HX_D2B locomotive blockade phenomenon caused by LFVF happened couples of times in Xu-Zhou north CRH substation in December, 2009. The corresponding LFVF waveform is shown in Fig. 1. Similar LFVF cases occur in Hudong substation, Nanxiang substation, Qingdao substation and so on in China [3].

Up to now, some researches about the LFVF of VGTS are conducted in electrical railway industry domain. On the stability analysis of the VGTS, a method is put forward on the basis of spot test [4], that is, the LFVF of VGTS is caused by the parameters mismatch between the locomotive and the traction network. While multi-locomotives are connected to the traction supply network, the LFVF phenomenon is analyzed in [5-7]. It is founded that the equivalent traction network impedance might become larger for the increasing numbers of locomotives. Besides, in [8-9], the VGTS stability in low frequency range is analyzed by the method of small signal, and the low-frequency oscillation is suppressed by modifying the rectifier control parameters. In addition, as for the control strategy of four-quadrant rectifier, equivalent model of CRH5 locomotives are established in [10]. The relationship between second order generalized integrator parameters, rectifier control parameters and system stability is analyzed as well. From the test which including several RE450 locomotives, [11] found that the PI parameters of the converter control system has a great influence on the voltage fluctuation of traction network, as well as the number of locomotives. In [12], to improve the ability of resisting LFVF for the locomotive converter, it is reported that appropriate PI control parameters can be selected via phase margin graph. The CRH5 locomotive is mainly considered in almost all the existing relevant researches, which controlled by the method of *dq*-decoupled strategy.

However, research on other kinds of VGTS, concluding traction supply network and electric locomotives (especially HX_D2B locomotives), is barely few. With more and more locomotives are put into operation, the chance of LFVF in the traction network which will lead to locomotive traction blockade is increasing. So, it is necessary to carry out several improved researches on LFVF.

In this paper, the mechanism of the tested waveform of the LFVF in northern Xu-zhou, in Fig. 1, is deeply investigated. The rest parts of paper are organized as follows. In section II, the mathematical description of traction power supply network and HX_D2B electric locomotive is completely established. In section III, the locomotive-grid system stability is analyzed by Nyquist stability criteria. In section IV, the simulation of LFVF phenomenon is carried out. The simulation is conformed to be validated by the comparison

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between simulated result and tested data from switch substation in northern Xu-zhou. Under the condition that multi-locomotives servicing prepare in a same feeder section, the stability analysis is conformed and discussed. Also, the relevant conclusions are drawn in Section V.

II. MATHEMATICAL DESCRIPTIONS OF VGTS

Based on lots of aforementioned analyses, The LFVF of VGTS may be a kind of stability problem. In order to simplify the research process, the VGTS is treated as a distributed power system, ie., the AT traction power supply network widely utilized in China VGTS forms a module by Thevenin theorem, and the locomotive rectifiers is another module. Two modules of VGTS are in series as shown in Fig. 2.

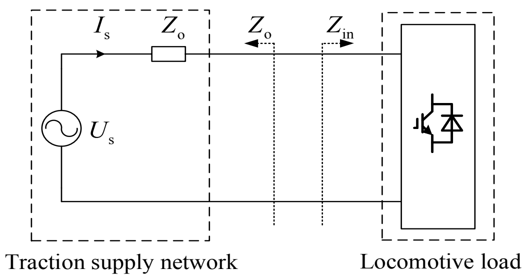

Fig. 2. The equivalent circuit of VGTS.

In Fig. 2, Z_o is the equivalent output impedance of AT traction network, Z_{in} represents the equivalent locomotive input impedance, U_s denotes the 27.5kV AC voltage source, I_s stands for the feeder current of traction substation.

A. Mathematical description of AT traction supply network

All-parallel double-tracked AT traction power supply network is widely used in China railway. At present, there are several methods of calculating AT traction network impedance, concluding equivalent circuit [13], the generalized symmetrical components [14] and so on. Based on the characteristics of up/down contact wire and positive feeder line, the VGTS system reveals symmetrical arrangement. With the AT leakage reactance is taken into account, a new symmetric components model of traction network is deduced in [15]. Corresponding complex circuit is depicted in Fig. 3.

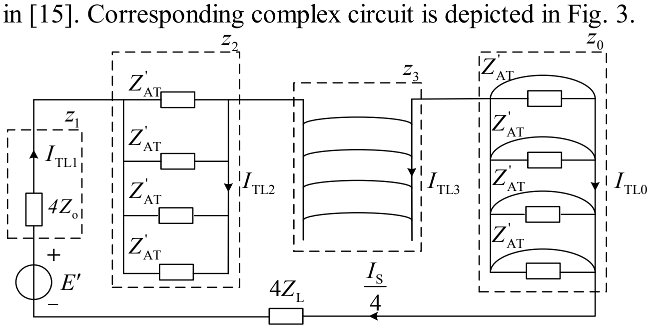

Fig. 3. The sequence network circuit of AT traction supply system.

In Fig. 3, E' denotes the 55kV ideal voltage source, $I_{TL0\sim4}$ represents the sequence current, $z_{0\sim4}$ is the sequence impedance, Z_L is the load impedance or short-circuit impedance. Here, the AT leakage reactance is expressed as.

$$Z_{AT}{}' = 2Z_{AT} \tag{1}$$

On the basis of [13], unit impedance transformation function matrix about double-tracked AT traction network was obtained in [15], which is

$$Z_{0123} = A_4^{-1} Z_{T_U F_U T_D F_D} A_4 \tag{2}$$

where T represents the contact wire and F represents the positive feeder line; U, D means uplink and downlink, respectively; A_4 is the unit transformation matrix.

The equivalent AT traction network output impedance can be acquired as

$$Z_o = Z_{eq} + Z_s \tag{3}$$

In (3), Z_{eq} denotes the equivalent traction network impedance, without traction transformer impedance taken into account. Z_s is the sum of traction transformer impedance and three-phase power grid impedance. Z_{eq} and Z_s are both mapped to the transformer secondary, ie., 27.5kV

For all-parallel double-tracked AT traction network, Z_{eq} can be expressed as [15]

$$Z_{eq} = \frac{1}{4}\left[\left(z_0 x + Z'_{AT}\right)\frac{z_0\left(D-x\right)+Z'_{AT}}{2Z'_{AT}+z_0 D} + z_1 l + \left(z_2+z_3\right)x\left(1-\frac{x}{D}\right)\right] \tag{4}$$

In (4), x is used to describe the position of the load in the AT segment, l represents the distance from the load to the head of the power supply arm, and D refers to the length of the rail between two AT segments.

In China, V/X traction transformer is widely utilized in AT traction power supply system. Consisting of three-phase power grid impedance and transformer winding leakage impedance, the total impedance of the V/X transformer primary side is mapped to the T-F port, ie., 55kV secondary side, signed by Z_{S1}, and Z_T, respectively. The equivalent circuit is shown in Fig. 4.

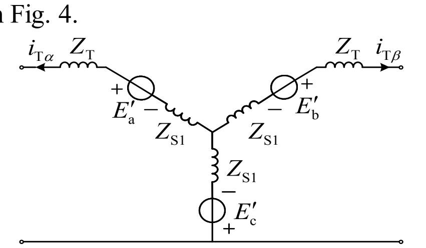

Fig. 4. The equivalent circuit of V/X traction transformer

Z_s is mapped to 27.5kV side and we can get

$$Z_S = \frac{1}{4}\left(2Z_{S1} + Z_T\right) \tag{5}$$

The electrical parameters of a traction substation are provided to meet the need of specific VGTS stability analysis in section III. The relevant parameters about Longgong traction supply substation in China Shuohuang railway [16] are shown in Table I.

TABLE I
LONGGONG TRACTION SUBSTATION PARAMETERS

Electrical quantity	Value
Capacity of three-phase short circuit, S_d	500MVA
Traction transformer capacity, S_T	75MVA
Percentage of the short-circuit voltage, U_d%	10.5
AT transformer leakage reactance, Z_{AT}	(0.04375 +j3.14) Ω