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Research on Robust Control for Electrified Railway Harmonic Suppression

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***Abstract*—Because of using the nonlinear high-power load, the electrified railway has serious harmonic problems. Aiming at the electrified railway power quality problems, this paper has established averaging active power filter model, and designed the H-infinity controller. Through containing all kinds of disturbance, ensure active power filter to approaching track complex current signal, thus improve the robustness of systems. Simulation results show that electrified railway harmonic control effect is good based on H-infinity control. Under parameter perturbation, THD relatively small changes, the system has strong robustness. In comparison with the hysteresis controller, H-infinity controller has a better control effect. Therefore, based on H-infinity control of active power filter in electrified railway harmonic control has wide application prospects.**

***Index Terms*—Power system control, Load management, power harmonic filters, railway.**

I. INTRODUCTION

China's electrified railway power supply adopts single-phase AC traction system. Most tractions using pulse stream DC motor by smoothing reactor to suppress current ripple. Working principle of AC-DC electric locomotives bring problems of low power factor, high harmonic current content. In recent years, we introduced some high-speed trains, with AC-DC-AC rectifying mode, which can basically solve the power factor and harmonic current issues of the locomotive side. But no matter what type of locomotive, the traction load is single phase or two-phase load, reflected in the three-phase AC side is asymmetric load, resulting in a large number of negative-sequence current. Electrified railway harmonic, reactive power and negative sequence are the important issue referring to electrified railway power quality problem [1]. As the train speed in rail transport, the increase of traffic density and load, the load of traction electric network is increasing, the influence of harmonic, reactive power and negative sequence on power system is also bigger, research on electrified railway quality on power systems and the influence of power system and electrified railway themselves are significant.

Solutions of electrified railway power quality problems include the comprehensive management of harmonic, reactive and negative sequence current. This paper, aims at power quality problems in electrified railways, the use of active power filter to suppress harmonics of the electric railway. Considering the electric traction's load is constantly changing, and other uncertain factors. In this paper, H-infinity controller design based on linear systems, through variety of interference suppression to ensure that the complex active power filter system asymptotically tracks the current signal of the complex instructions to improve the robustness of the system.

II. ANALYSIS ON HARMONIC CONTROL METHODS OF ELECTRIC RAILWAY

Control of electric railway harmonic method is divided into two kinds of active-and passive. Active done is to try to make the harmonic as few as possible, while finish the main function of the task. Passivity means various passive power filter and active power filter and harmonic compensation devices etc, which are installed in bus bar. Because in decades, china has produced a large number of AC/DC pattern electric locomotives, and the AC/DC pattern still has the majority in electric locomotives which are producing. So for a long time, they still occupy the main status in our country railway transportation. Therefore, in addition to changing the feeder parameters to enhance harmonic capability of the traction power supply system, a variety of filtering devices on the installation in traction transformers 27.5kV bus bar has been the main measure to control the electric railway harmonic.

Usually, power capacitors, reactors and resistors are adopted to form a passive power filter in accordance with the functional requirements. The device, which shows a low resistance path for the harmonics, effectively plays a filtering effect of the harmonic filter.

Passive filter can not only play a filter role, but also do reactive power compensation. Although the passive filter has a simple structure, low cost, easy maintenance, high harmonic filtering effect and other obvious advantages, there are some difficulties to overcome the shortcomings.

Some idle work compensation systems also can be able to play the harmonic suppression role. For example, parallel fixed capacitors group and in series of 12% of the reactors, also play a role in harmonic suppression, while do the reactive power compensation [2]. Another example, parallel magnetic saturation reactor on the basis of fixed capacitor compensation equipment, according to the calculated load of

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reactive power or the size of power factor to control the size of the thyristor, adjust magnetically controlled reactor through the thyristor to pour into the 27.5kV bus bar inductive reactive power. The realization has allowed the capacitive reactive power with the compensation to counterbalance, to achieve the harmonic control and reactive power compensation purposes. In the design concept, these compensation devices are mainly for reactive power compensation, and have some functions of filtering 3rd, 5th and 7th harmonic. In actual operation, the average power factor can basically meet the national standard requirement. When the load is small, there are different degrees of capacitive reactive anti-sent. And harmonics far exceeded, when the load is larger.

With the full-controlled power device technology advance and more and more sensitive load increasing the demand for the effect of filtering, active power filters started by people's attention. Through producing the current with the same shape, the opponent phase compared to the compensation harmonic, it can offset the harmonic currents produced by nonlinear loads. APF is a new power electronic device used for dynamic harmonic suppression, reactive power compensation. It can compensate harmonic with changing size and frequency and variable reactive power. The application can overcome shortcomings of LC passive power filter and other traditional harmonic suppression methods [3].

III. BASIC CONCEPT OF H-INFINITY CONTROL FOR LINEAR SYSTEMS

A. *Linear systems based on H-infinity control*

The perturbed and controlled linear systems can be described to be a state-space like (1) to form a hypothesis:

$$\begin{cases} x = Ax + B_1 w + B_2 u, \\ z = C_1 x + D_{11} w + D_{12} u, \\ y = C_2 x + D_{21} w + D_{22} u, \end{cases} \qquad (1)$$

There, $x \in R^n$ is a state vector, $u \in R^m$ is used to control the input vector, $y \in R^p$ is seen as measure the output vector, $z \in R^r$ is used to evaluate the output vector, and $w \in R^q$ is considered external disturbance vector ($w \in L_2[0,+\infty]R^q$). Every vector and matrix is differentiable to the full [4].

Designing a controller ($u(s) = K(s)y(s)$), making the closed-loop system has the following features.

The closed-loop system is stable inside. All of the closed-loop system state proper values of matrix are in the left half open complex planar.

The H-infinity norm of the closed-loop transfer function $T_{wz}(s)$ from the input disturbance w to the controlled output z is less than 1. It means $\|T_{wz}(s)\| < 1$. So the controller $u(s) = K(s)y(s)$ with these properties called H-infinity system controller [5].

If the system model of the coefficient matrix were multiplied by a proper constant, the closed-loop system can has the function γ of giving H-infinity. It means that the H-infinity controls problem $\|T_{wz}(s)\| < \gamma$ can be translated into the standard H-infinity control problem which makes $\|T_{wz}(s)\| < 1$.The standard H-infinity sketches as shown Fig. 1. The controller that has the function γ of giving H-infinity is called γ subprime controller of the system [6].

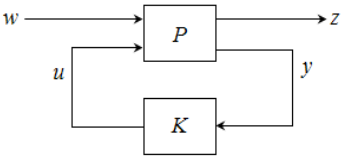

Fig. 1. Standard H-infinity control schemes.

B. *Linear Matrix Inequality Based on H-infinity Control*

Linear matrix inequality (LMI) is more and more attracted wide public concern and view, which it is gained widespread recognition and application on H-infinity control and analysis and design of the performance. A linear matrix inequality is an expression like

$$F(x) = F_0 + x_1 F_1 + \cdots x_m F_m < 0 . \qquad (2)$$

Among them, x_1, … x_m, that are real variable of with a number of m, which are called LMI policy variable. $x = (x_1, \cdots x_m)^T \in R^m$, it is the vector that made of policy variable. It is called decision-making vector. $F_i = F_i^T \in R^{n \times n}$, $i =$ 0, 1, 2, m is a set of given real symmetrical matrix [7].

When LMI method is used to calculate the control laws of linear system H-infinity, system is shown as follows:

$$\begin{cases} x(t) = Ax(t) + Bw(t), \\ z(t) = Cx(t) + Dw(t). \end{cases} \qquad (3)$$

In (3), $x(t) \in R_n$, $w(t) \in R_q$ and $z(t) \in R_r$ are respectively the system state, the input and output of the system. Supposing constant $\gamma > 0$, then system is asymptotically stable, and in closed loop transfer function, $\|T_{wz}(s)\|_\infty < \gamma$, if and only if it exist a symmetric matrix $P > 0$, satisfy

$$\begin{bmatrix} A^T P + PA & PB & C^T \\ * & -\gamma I & D^T \\ * & * & -\gamma I \end{bmatrix} < 0 . \qquad (4)$$

In this paper, the "$*$"of block matrix $\begin{bmatrix} A & B \\ * & C \end{bmatrix} < 0$ specify the symmetry of the blocks.

IV. ESTABLISHMENT OF ACTIVE POWER FILTER AVERAGING MODEL

Active power filter mainly contains four links, instructions current operation circuit, the current tracking control circuit, inverter driving circuit and inverter constitute the main circuit. Its purpose is to make inverter produce required compensation of harmonic and reactive current, and maintaining a dynamic stability of DC capacitor voltage. Its main circuit is shown in Fig. 2.

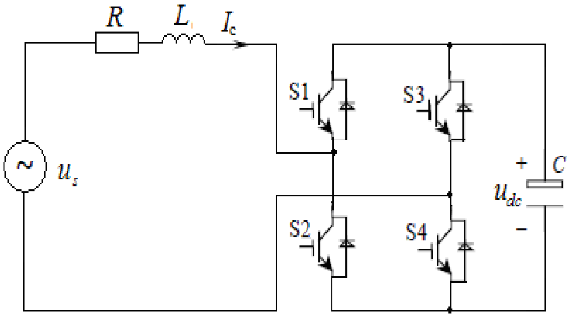

Fig. 2. The main circuit diagram of the inverter.

In the main circuit, u_s is a power supply voltage, the active power loss and inverter switching loss are replaced by *R*. The main circuit and the reactance in filter circuit can be replaced by an equivalent inductance *L*. Harmonic source load contains base wave active electric current i_{1f} , harmonic and reactive current i_{1h}. Suppose that the filter output a current i_c which has the same size and the different direction with the current i_{1h}, so the supply current just contains the base wave active weight i_{1f} of the load current. According to the circuit model can get the following equations [8]:

$$\begin{cases} L\dfrac{di_c}{dt} = -Ri_c - su_{dc} + u_s, \\ C\dfrac{du_{dc}}{dt} = -si_c. \end{cases} \tag{5}$$

Among them, s is the switch function. When it is equal to one, it means opening the up bridge-arm, shutting off the down bridge-arm. And when it is equal to zero, it means opening the down bridge-arm, shutting off the up bridge-arm.

For the convenience of the equal distributions for modeling process, s is replaced by the equivalent variable d . So, s is expressed as $s = (d+1)/2$.

Put the s into (5) to get the APF system state equation:

$$\begin{cases} L\dfrac{di_c}{dt} = -Ri_c - \dfrac{d+1}{2}u_{dc} + u_s, \\ C\dfrac{du_{dc}}{dt} = -\dfrac{d+1}{2}i_c. \end{cases} \tag{6}$$

Using the ordinary average modeling method can get the homogenization system state equation of APF:

$$\begin{cases} L\dfrac{di_c}{dt} = -Ri_c - \dfrac{p+1}{2}u_{dc} + u_s, \\ C\dfrac{du_{dc}}{dt} = -\dfrac{p+1}{2}i_c. \end{cases} \tag{7}$$

Among them, $p(t) \in [-1,1]$ is control variable under average model.

When the system of compensation to the balance, system voltage, current should be:

$$u_s = U_m \sin(\omega t + \phi), \tag{8}$$

$$i_s^* = I_m \sin(\omega t + \phi). \tag{9}$$

Among them, U_m is base amplitude, i_s^* is ideal current, which can be get from (10)

$$I_m = k_p(u_{dc} - U_{dc}) + k_i \int (u_{dc} - U_{dc})dt. \tag{10}$$

Among them, U_{dc} is expressed as the capacitor reference voltage value of the DC voltage side.

Because of the formula $i_s = i_1 + i_c$, when it is become the electric current's ideal value, the need of the electric current's compensation dosage which produced by the filter is $i_c^* = i_s^* + i_1$.

According to the model above-mentioned, the single-phase parallel active power filter's H-infinity control model can be:

$$\begin{cases} \dfrac{di_c}{dt} = -\dfrac{R}{L}i_c - \dfrac{p}{2L}u_{dc} + \dfrac{2u_s - u_{dc}}{2L} + w, \\ z' = i_c + w, \\ y' = i_c - i_c^*. \end{cases} \tag{11}$$

Supposing $x' = i_c$, $x_1 = \dfrac{2u_s - u_{dc}}{2R}$, $y_1 = x_1 - i_c^*$, $x = x' - x_1$, $y = y' - y_1$, $z = z' - x_1$, then, the H-infinity control model's standard model is got. So this model's output feedback controller can be

$$u = K(s)y. \tag{12}$$

V. SIMULATION ANALYSIS

MATLAB simulation model is shown in the following Fig. 3. The QIANYIN module reflects the traction power supply system. The XIEBOJIANCE acts as for harmonic detection module. The SANJIAOZAIBO-KONGZHI mirrors the current hysteresis control module. Subsystem2 is for inverter main circuit, and K is the H-infinity controller.

In both cases of H-infinity control and hysteresis control, when *L*, *R* and *C* are added 0.0005H and 0.5Ω and 0.0001F respectively, harmonics wave are FFT analyzed. The summary of two kinds of condition likes Table I.

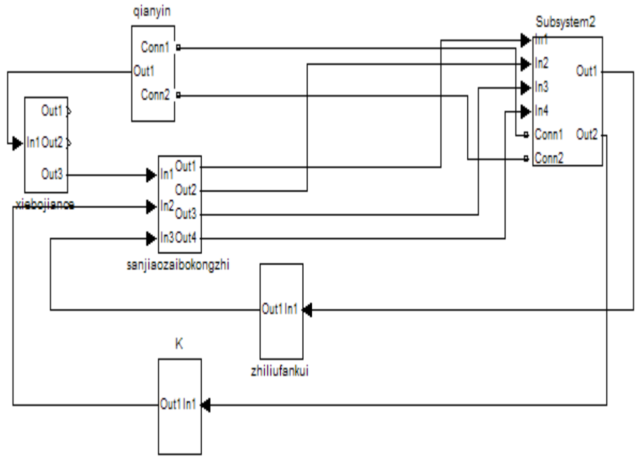

Fig. 3. Simulated model of active wave filter.

TABLE I. THE COMPARE OF EFFECT OF CONTROL.

	H-infinity Control (THD)	**Relative change**	**Hysteresis control (THD)**	**Relative change**
Parameters don't change	**2.58**		**2.53**	
ΔR	2.64	2.32	2.59	2.37
ΔL	2.94	13.95	3.17	25.3
ΔC	2.57	0.39	2.5	1.19
ΔR+ΔL	2.99	15.89	3.22	27.27
ΔR+ΔL+ΔC	2.85	10.47	3.02	19.37

We can see from the above-mentioned. The effect is good when H-infinity control the harmonic restrains. And H-infinity control is better than hysteresis control. Tabel1 has sufficiently embodied that H-infinity controller having the fairly good stability and robustness.

VI. CONCLUSIONS

In electrification railroad harmonic suppression, the active power filter has the vast application prospect. Through the active power filter establish averaging model, and analysis and calculating the robustness of the active power filter are carried out owing to H-infinity control theory. Simulated analysis indicates that the effect is good when H-infinity controls the electrification railroad harmonic suppression. And when parameter is done perturbation motion, the relative change of THD is little. The system can follow the change of load very good. This has sufficiently embodied that H-infinity controller having the fairly good stability and robustness.

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