Research on Robust Control Strategies for VSC-HVDC

Kaicheng Zhu, Hai Bao

School of Electrical & Electronic Engineering, North China Electric Power University, Beijing 102206, China

Corresponding author e-mail: 295429165@qq.com

Abstract. In the control system of VSC-HVDC, the phase locked loop provides phase signals to voltage vector control and trigger pulses to generate the required reference phase. The PLL is a typical second-order system. When the system is in an unstable state, it will oscillate, make the trigger angle shift, produce harmonic, and make active power and reactive power coupled. Thus, considering the external disturbances introduced by the PLL in VSC-HVDC control system, the parameter perturbations of the controller and the model uncertainties, a $H_\infty$ robust controller of mixed sensitivity optimization problem is designed by using the Hinf function provided by the robust control toolbox. Then, compare it with the proportional integral controller through the MATLAB simulation experiment. By contrast, when the $H_\infty$ robust controller is added, active and reactive power of the converter station can track the change of reference values more accurately and quickly, and reduce overshoot. When the step change of active and reactive power occurs, mutual influence is reduced and better independent regulation is achieved.

1. Introduction

High voltage direct current transmission (VSC-HVDC) based on voltage source converter (VSC) is a new type of direct current transmission technology. Its core is the use of a fully controlled power electronic device VSC instead of the conventional thermistor converter [1].

Because of the external disturbance introduced by PLL, the parameter perturbation of the controller and the uncertainty of the model, VSC-HVDC system has difficulty in dynamic control. In document [2] an additional damping controller is designed through pole placement. In literature [3] the controller is designed by lead lag method. These methods, based on PI control, are very difficult to improve the control effect. Therefore, a $H_\infty$ robust controller for the overall system with current decoupled controller was designed, and the effectiveness of the controller is verified by simulation results.

2. Introduction of VSC-HVDC control system

2.1. AC/DC converter mathematical model

According to reference [4], VSC mathematical model based on Park transform in d-q synchronous rotating coordinate can be obtained:
In the formula, $\omega$ is the synchronous angular frequency, $M$ is the modulation ratio, $\delta$ is the trigger angle, $u_{sd}, u_{sq}$ are the power side voltage, and $i_d, i_q$ are the current, the equivalent resistance and equivalent inductance of transformer and phase reactor are $R$ and $L$.

Since the three-phase symmetrical AC system has no zero sequence component, when grid voltage vector is positioned by d axis $u_{sq} = 0$. The active and reactive power delivered to the grid are:

$$P_s = \frac{3}{2} (u_{sd} i_d + u_{sq} i_q) = \frac{3}{2} u_{sd} i_d$$
$$Q_s = -\frac{3}{2} (u_{sd} i_q - u_{sq} i_d) = -\frac{3}{2} u_{sd} i_q$$

In the formula, $u_{sd}$ is a constant value, formula (2) shows that if change the $i_d, i_q$, the delivered power will change.

### 2.2. Power controller model

AC/DC converter adopts double closed loop controller [4]. The outer loop controller is used to realize different control strategies, and the inner loop control is used to improve the power quality through fine adjustment. Considering $u_{sq} = 0$, according to formula (2), we have:

$$u_{sd} = u_{sd} - R i_d - L \frac{di_d}{dt} + \omega L i_q$$
$$u_{sq} = -R i_q - L \frac{di_q}{dt} - \omega L i_d$$

According to formula (3) and for the goal of decoupling, the controller model can be obtained, as shown in Figure 1.
According to formula (3) and Figure 1, a converter system diagram based on a synchronous rotating coordinate can be obtained, as shown in image below:

![Figure 1](image_url)

**Figure 1.** Block diagram of the power controller.

The analysis shows that when the triggering signal is correct, we can control the converter’s active and reactive power accurately and decoupled. But PLL is a typical second-order system. When the system is in unstable state, it will oscillate, make the trigger angle shift, produce harmonic, and make active and reactive power coupled.

2.3. **PLL operating principle**

PLL is a typical second-order system whose output signal’s phase is consistent with input signal’s phase [5]. The mathematical model is shown in Figure 3.
In the picture, $\theta_i(s)$ is the phase of the input signal. $\theta_o(s)$ is the phase of the output signal. $\theta_{fb}(s)$ is the phase of the feedback signal. $K_d$ is the gain of phase discriminator. $K$ is the gain of the voltage controlled oscillator. $N$ is the frequency division ratio of the frequency divider. RC integral filter is used as loop filter. So $F(s) = 1/(\tau s + 1)$. The transfer function of PLL is:

$$H(s) = \frac{\theta_o(s)}{\theta_i(s)} = \frac{K_d K_o / \tau}{s^2 + s / \tau + K_d K_o / (\tau N)} = \frac{N \omega_n^2}{s^2 + 2 \xi \omega_n s + \omega_n^2}$$

(4)

According to document [6], when an exponential decaying signal is input to the PLL, the frequency of the output signal is not exponentially damped, but oscillatory decay. During the adjustment of active and reactive power, there will be an exponential decaying signal in voltage, while the output signal of the PLL is oscillatory decaying. That will make the trigger angle shift, produce harmonic, and make active power and reactive power coupled. To solve this problem, a robust controller is added to the converter system.

3. Robust control principle and design of robust controller

Taking these into account: 1. the disturbance $d$ introduced by PLL. 2. Uncertainty of model parameters of converter station. Above problems are consistent with the mixed sensitivity problem in robust control theory. Therefore, in order to control the disturbance effectively and take the uncertainty of the parameters of the control model into account, we designed a robust controller under the mixed sensitivity optimization problem.

3.1. $H_\infty$ Standard control problem

Due to the change of working conditions, external disturbances, unmodeled errors and various faults of the system, etc. There is uncertainty in the mathematical model of the object. When the system has some uncertain parameters and a certain limit of unmodeled dynamics, we can stabilize the closed-loop system through design that is robust control [7].

$H_\infty$ Robust control theory takes the norm of the evaluation function as the performance index, and obtains the controller with robust performance by optimizing the norm. In the design of $H_\infty$ controller, the mathematical model of the controlled object must be established. Then, the model is transformed into a controlled object model corresponding to the standard control problem. Finally, the $H_\infty$ controller is designed according to the solution of standard control problem.

3.2. The optimization problem of mixed sensitivity

The standard model of the mixed sensitivity optimization problem.
Figure 4. The standard model of mixed sensitivity optimization problem.

Among them, \( r \) is the input signal, \( e \) is the error signal, \( K \) is the controller to be designed, \( G \) is the system transfer function, \( d \) is the system disturbance, \( W_1, W_2, W_3 \) is weighting functions designed to improve the system index.

The closed loop transfer functions from \( r \) to \( e \), \( u \), and \( y \) are

\[
\begin{align*}
S &= (I + GK)^{-1}, \\
R &= K(1 + GK)^{-1}, \\
T &= G(1 + GK)^{-1}
\end{align*}
\]

respectively. Select the target function

\[
P = \begin{bmatrix} W_1S \\ W_2R \\ W_3T \end{bmatrix},
\]

then we need to find a function \( K \) (controller) which can stabilize the system, and \( \|P\|_\infty < 1 \).

3.3. The solution of \( H_{\infty} \) robust controller

To get the robust controller, the model of converter system needs to be transformed into a unit feedback system. First of all, in the simulation system designed by Figure 2, it is found that active and reactive power can’t track the reference value quickly. To enhance the effect of reference signals, adjust as follows: the first proportional integral regulator PI is changed into an integrator, and the power reference value is directly added to the signal after the integrator acts. The PLL provides a reference phase to generate trigger pulses which are abstracted as transfer function \( K \). When the system operates in steady state, \( K=1 \). After current decoupling control is adopted, we can separate the current controller into two independent control loops of \( d \) axis and \( q \) axis. When the system is in an unsteady state, PLL oscillated, the transfer function of \( K \) will not be equal to 1, active and reactive power control will be coupled, and perturbation \( d \) appears. Then system of Figure 2 will be (reactive power is similar to active power):

Figure 5. The structure of control system of converter after disturbance extracted.

Among which, \( d = \left(\frac{1}{K} - 1\right) \frac{1}{K_p + \frac{1}{K_i}} (u_{sd} + \omega L_{sq}) \) is the cause of coupling.

In order to meet the standard model of mixed sensitivity optimization problem, the system is transformed into a unit feedback system:
Figure 6. The converter station system is converted into unit feedback system.

Among which:

\[
G = \frac{G_1 K_G s}{1 + G_1 K_G}
\]

\[
G_1 = K_p + \frac{K_i}{s}
\]

\[
G_2 = \frac{1}{sL + R} = \frac{1}{0.3s + 0.0065}
\]

\[
G_{all} = \frac{(1 + \frac{20}{s})}{2(1 + G_1 K_G)}
\]

After making \( K \) equal to 1 and substituting the parameter:

\[
G_{all} = \frac{9s^2 + 189s + 180}{0.6s^3 - 2.987s^2 - 3s}
\]

\( W_1(s) \) is the weight function of sensitivity function \( S \). In the design, the sensitivity function is required to be as small as possible, so that the tracking error can be reduced and the influence of interference can be effectively suppressed. Select:

\[
W_1(s) = \frac{100(0.005s + 1)^2}{(0.2s + 1)^2}
\]

To limit the size of control signal, we introduced weight function \( W_2(s) \), which can prevent saturation of the system and reduce the damage caused by the excessive amount of the actuator. Choose:

\[
W_2(s) = 0
\]

\( W_3(s) \) represents the upper bound of multiplicative uncertainty of the converter model, and must be the real rational function. Choose:
After the weight functions are selected, the robust controller can be obtained by adding $G_{all}$ into the $H_{inf}$ function of the MATLAB robust control toolbox [8]. Eventually get:

$$G_c = \frac{17.49s^4 + 7130.38s^3 + 747910.84s^2 + 4725357.87s + 3504454.06}{s^4 + 30.93s^3 + 254.23s^2 + 722.55s + 498.25}$$

(10)

4. Simulation Analysis
The $H_{inf}$ robust controller is added to the converter system.

![Diagram](image)

**Figure 7.** The robust controller is added to the converter system after deformation.

But the system is a deformed converter station system, needs to find the position of the original system for the robust controller. Therefore, set the integral function of the original system to $x$, and get the input and output equations of the two systems:

$$\begin{align*}
\begin{bmatrix}
P_{ref} - P \end{bmatrix} x + P_{ref} G_{all} &= P \\
\frac{G_{all} \left( \frac{1 + K_i}{s} \right)}{1 - G_{all}} G_c &= P
\end{align*}
(11)
$$

We have:

$$x = G_i + G_i \frac{K_i}{s} - 1$$

(12)

So the $H_{inf}$ robust controller is added to the position shown in Figure 8.
In order to analyse and verify the steady-state performance and dynamic response of VSC-HVDC system after adding the robust controller. In the simulation process, when the system is stable, the reference value of power are step changed, and the dynamic step response is observed (k=1.1).

At 1.3s, the active power reaches a steady value of 1pu, and the reactive power reaches the set value of 0pu and remains stable. When the system is stable, make the reference value step changed for -0.1pu at 1.5s and 2.5s respectively. In the two cases, the system response of the converter station is shown in Figure 9 and Figure 10.

By contrast we can know that after the robust controller is added, the active and reactive power of the converter station can track the change of reference value more accurately and rapidly, and the overshoot is obviously reduced. When a step change of -0.1 is added, the fluctuation caused by another value can be obviously reduced, which shows that the controller can realize the independent regulation of active and reactive power.

5. Summary
In this paper, the mathematical model of VSC-HVDC control system is analysed. Considering the uncertainty of the model parameters and the disturbance caused by PLL, Using the Hinf function provided by the robust control toolbox, we designed a robust controller under the mixed sensitivity.
optimization model, and the controller is simulated and verified. Simulation results shows that, in step change, the controller can control active and reactive power independently, make them track reference values fast, and weaken the influence of each other.

6. References

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